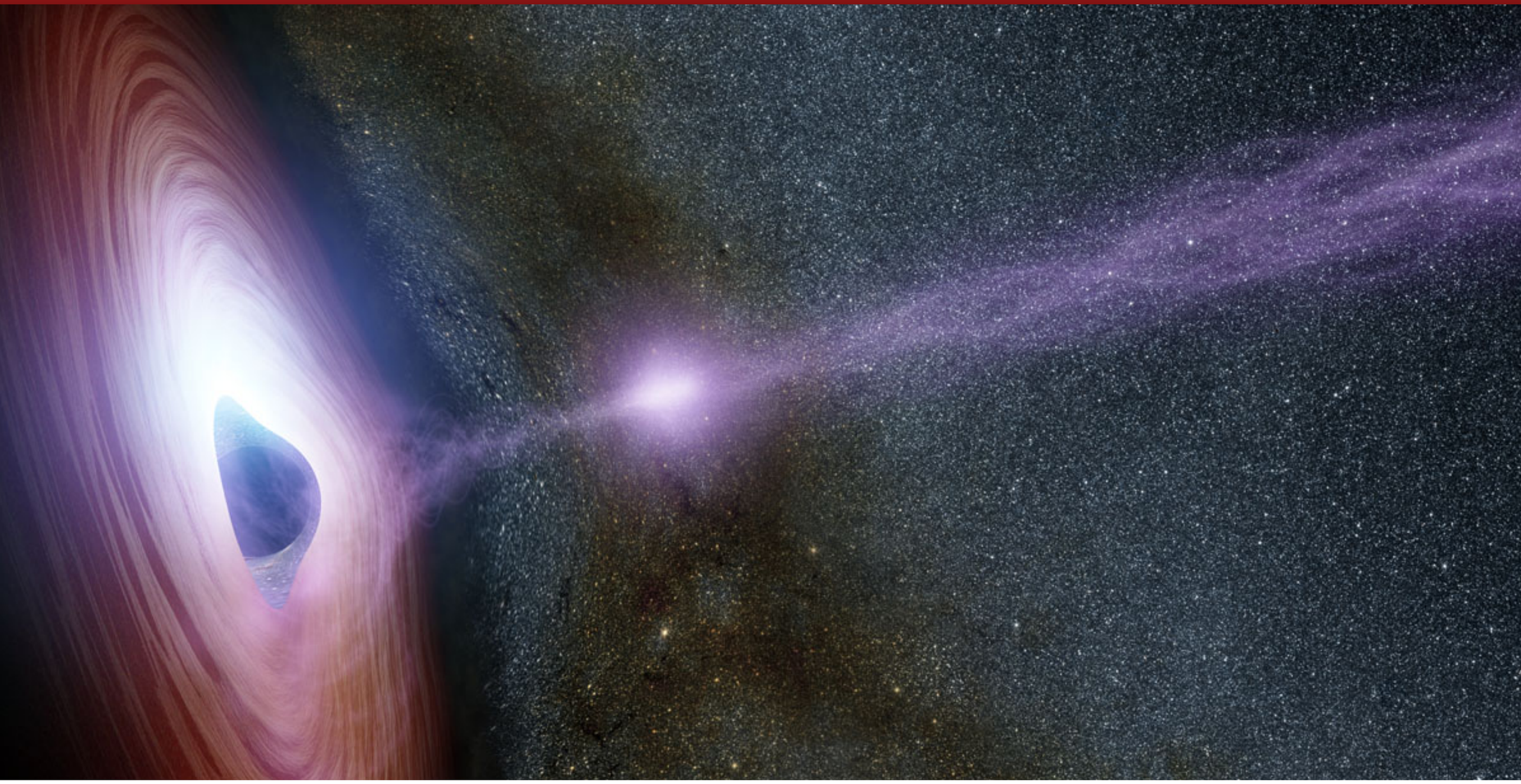


Observing Black Holes

Dr Dan Wilkins

PHYSICS 100 – Introduction to Observational Astrophysics

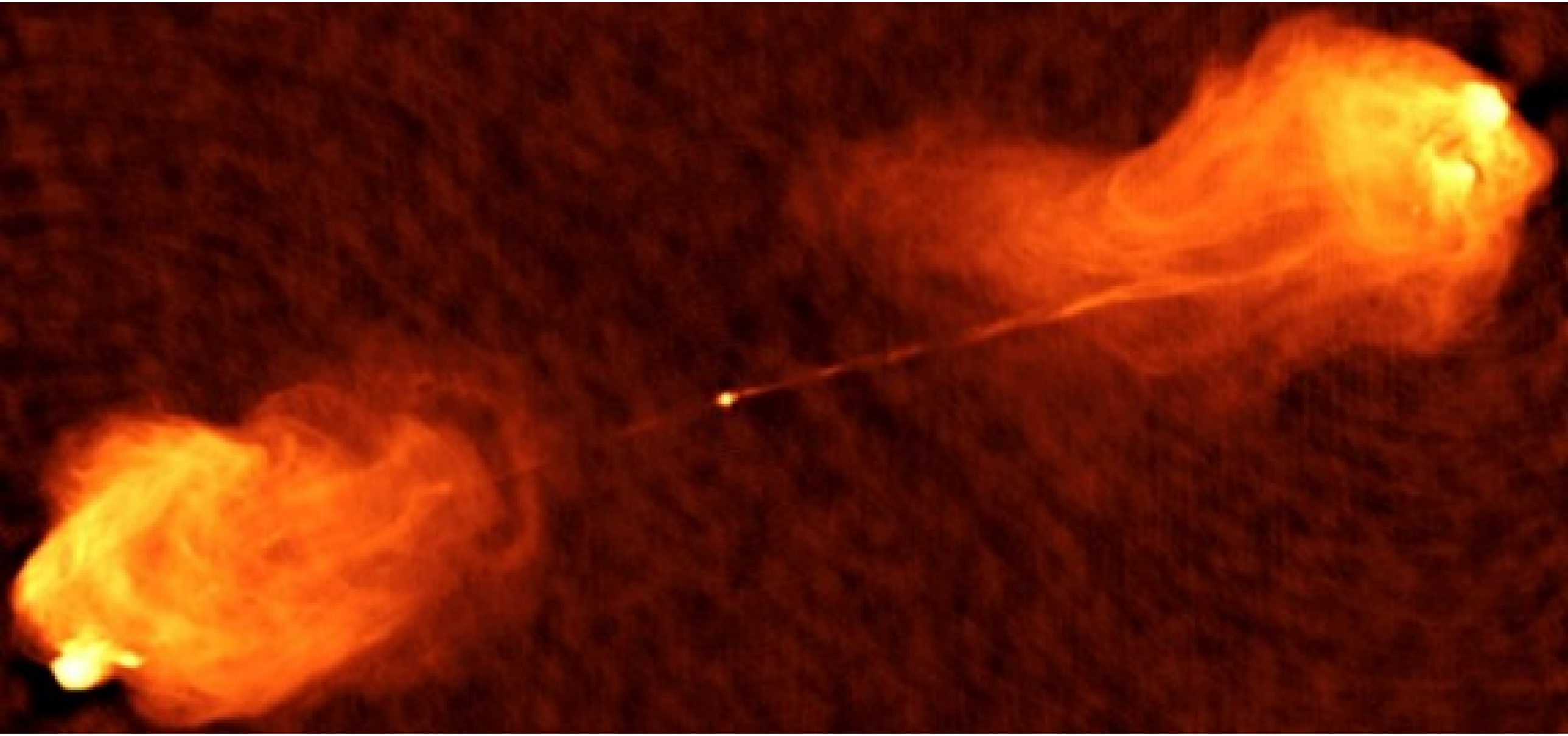
Outline

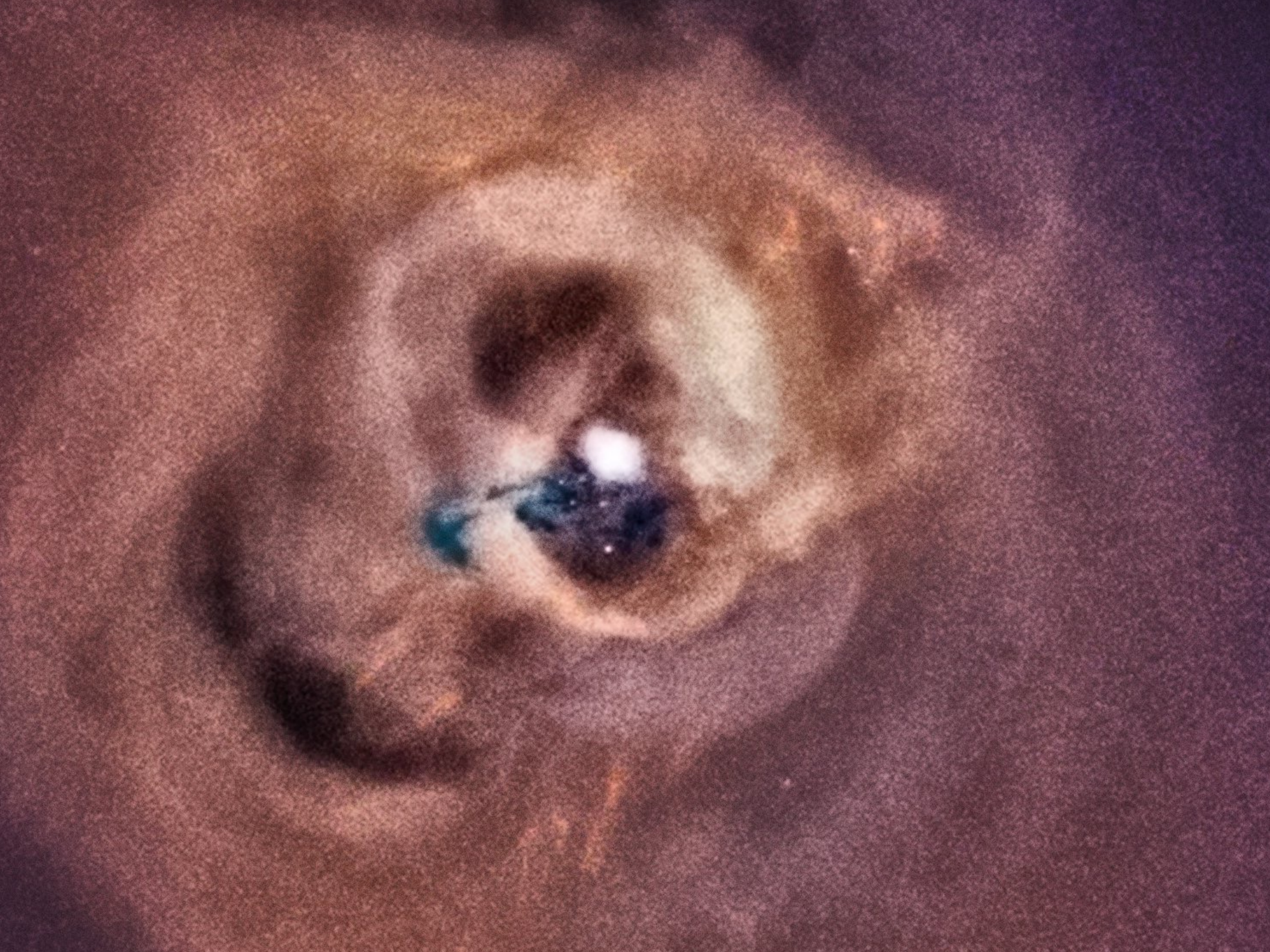
- Where do we see black holes?
- Anatomy of a black hole
- Powering the light source
- Measuring properties of a black hole

Active Galactic Nuclei

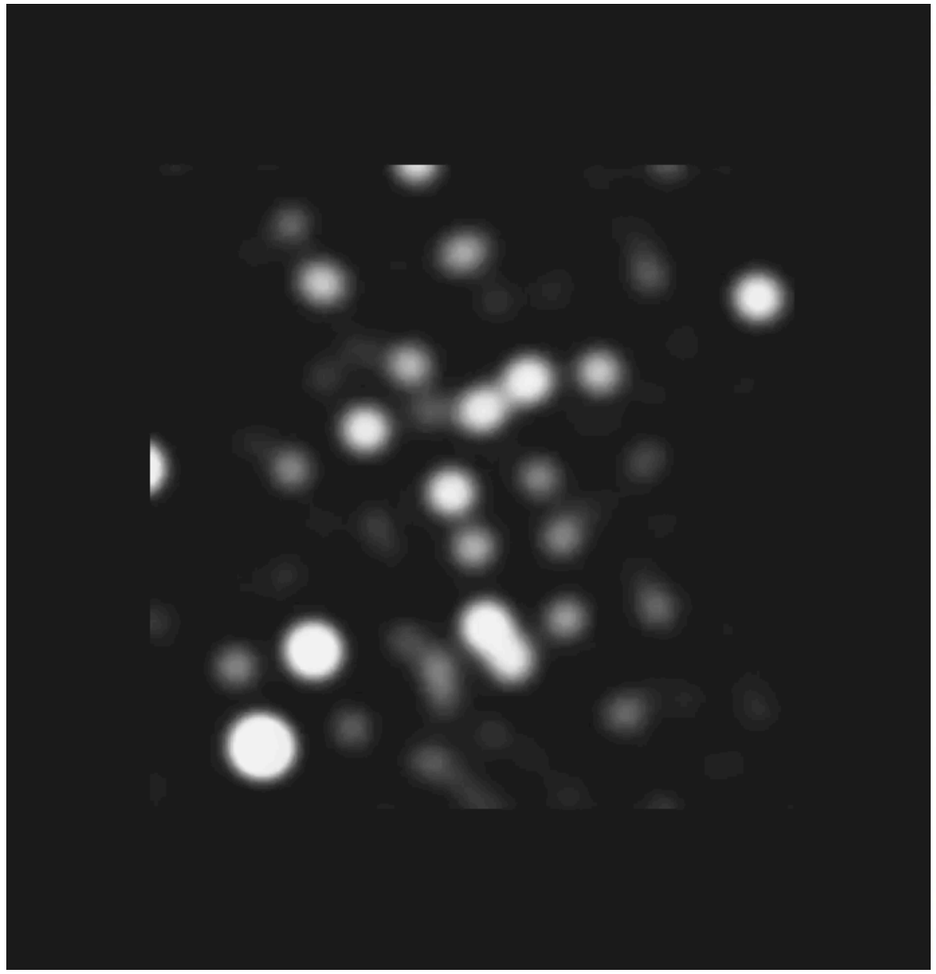
$$M = 10^6 \sim 10^9 M_\odot$$

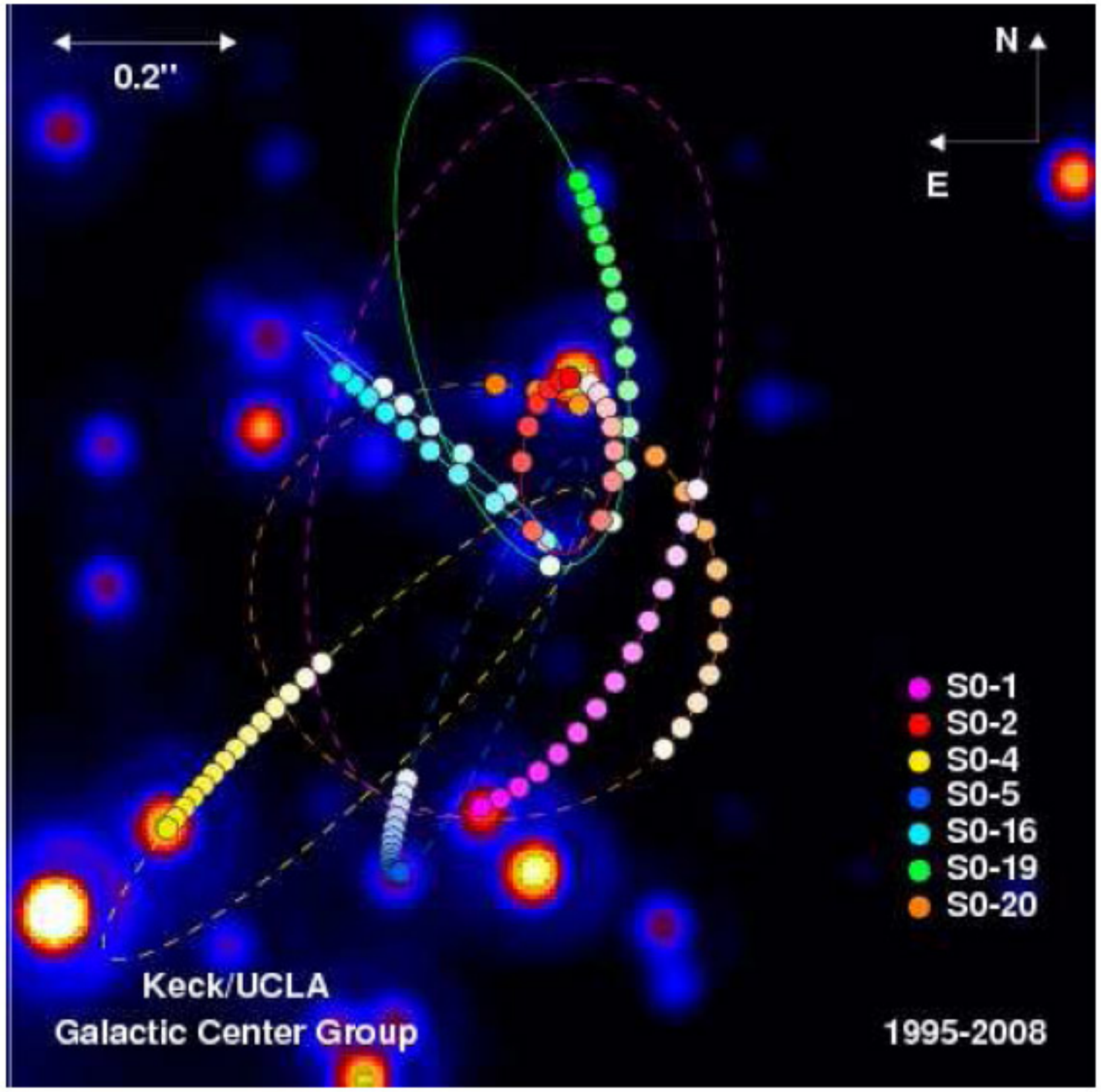
$$L_{\rm nuc} \sim 10^{44}\,{\rm erg\,s^{-1}} \sim 10^{11} L_\odot$$





The Galactic Centre (Sgr A*)





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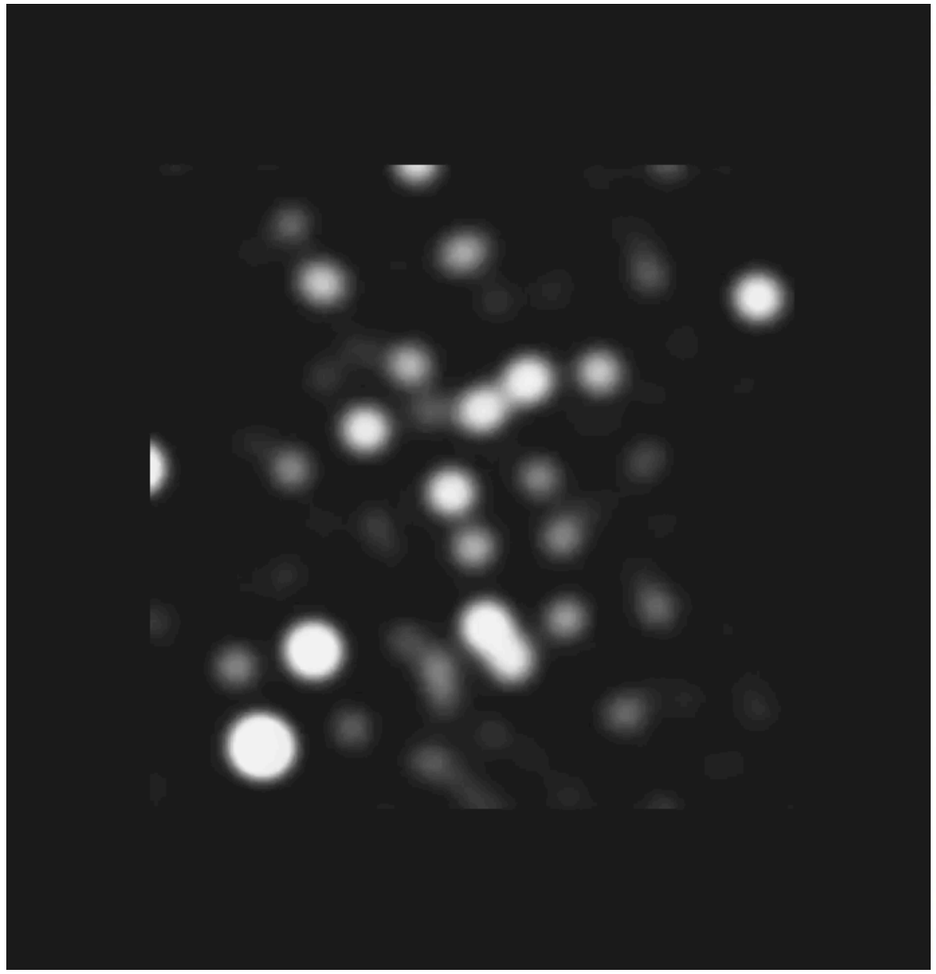
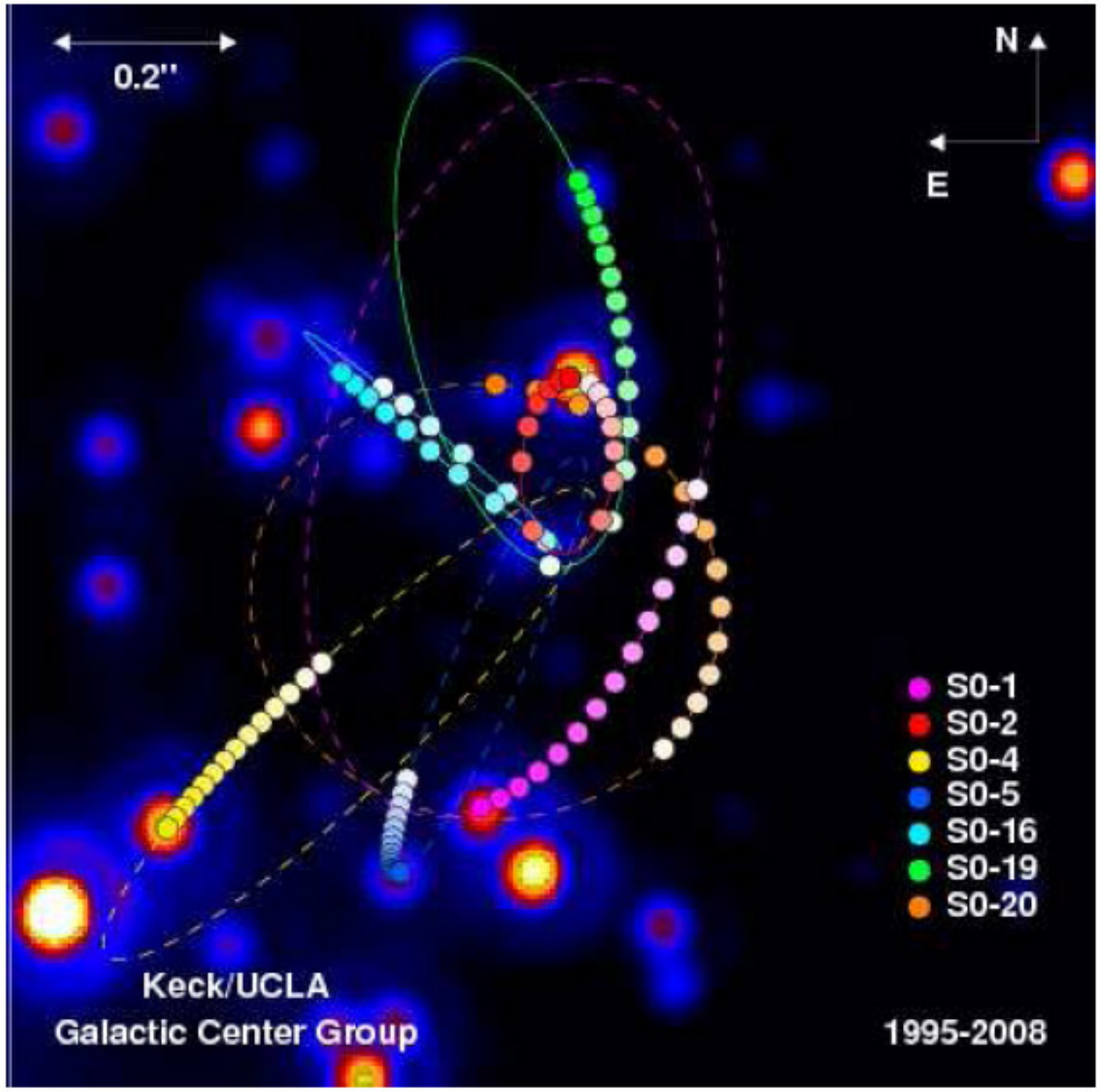
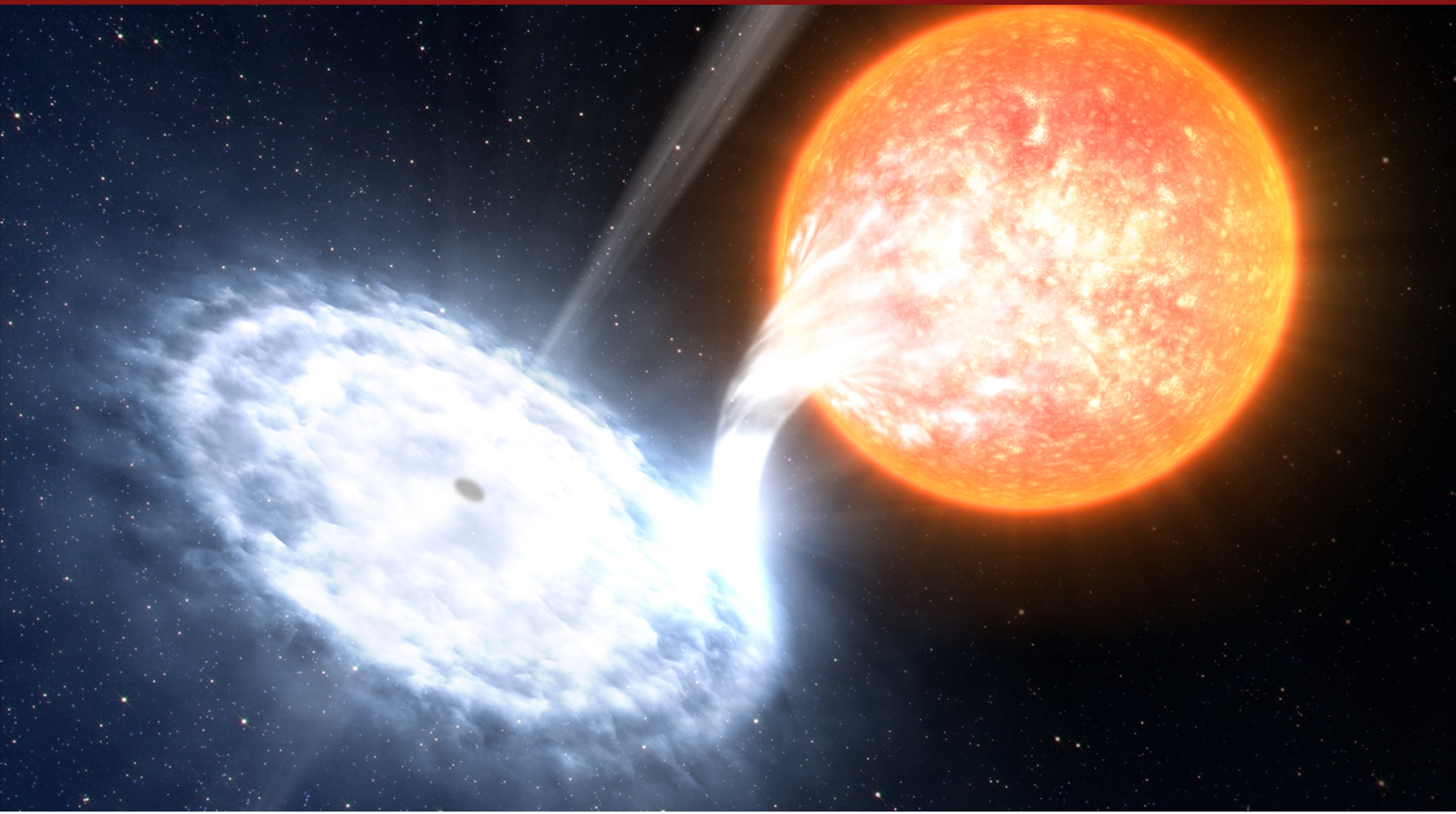




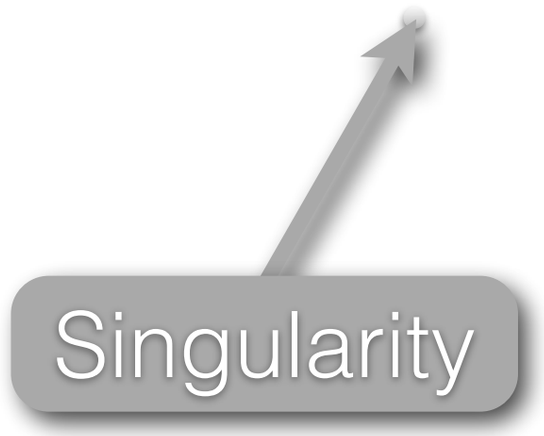


Stellar Mass Black Holes

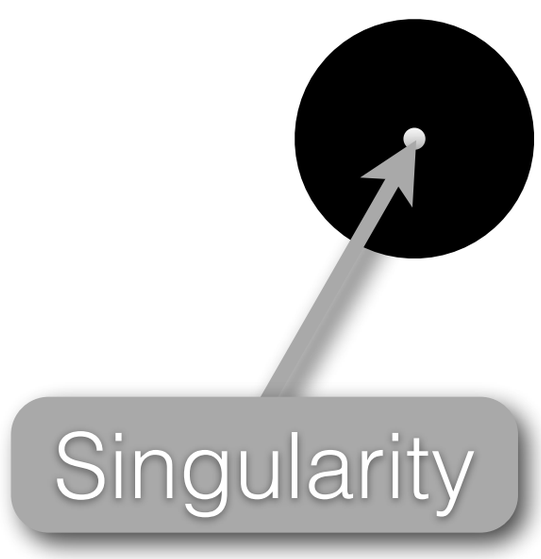
$$M = 1.5 \sim 10\, M_\odot$$

Anatomy of a Black Hole

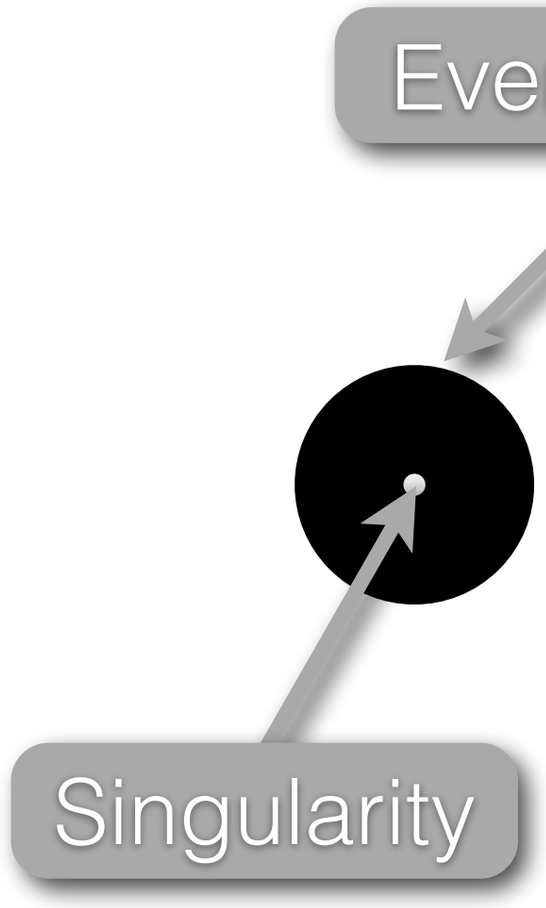
Anatomy of a Black Hole



Anatomy of a Black Hole

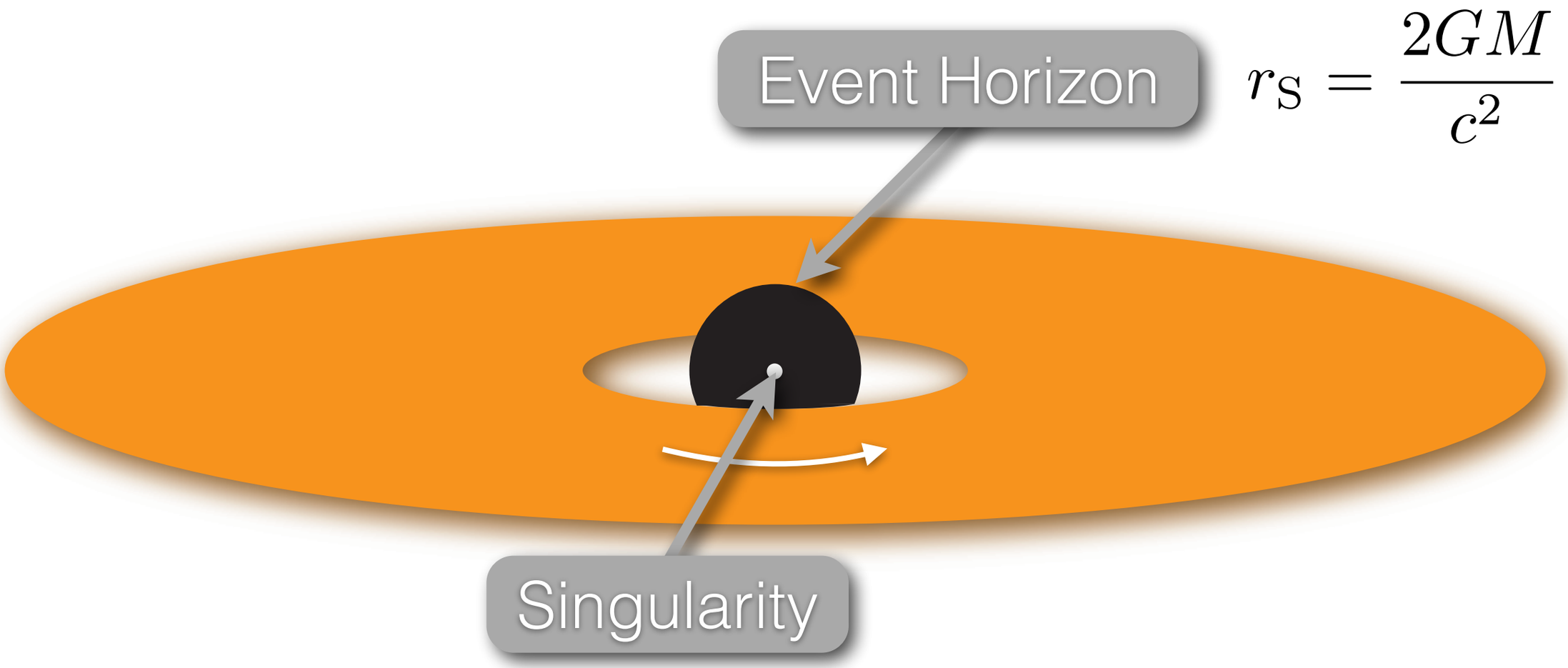


Anatomy of a Black Hole



$$r_{\mathrm{S}} = \frac{2GM}{c^2}$$

Anatomy of a Black Hole



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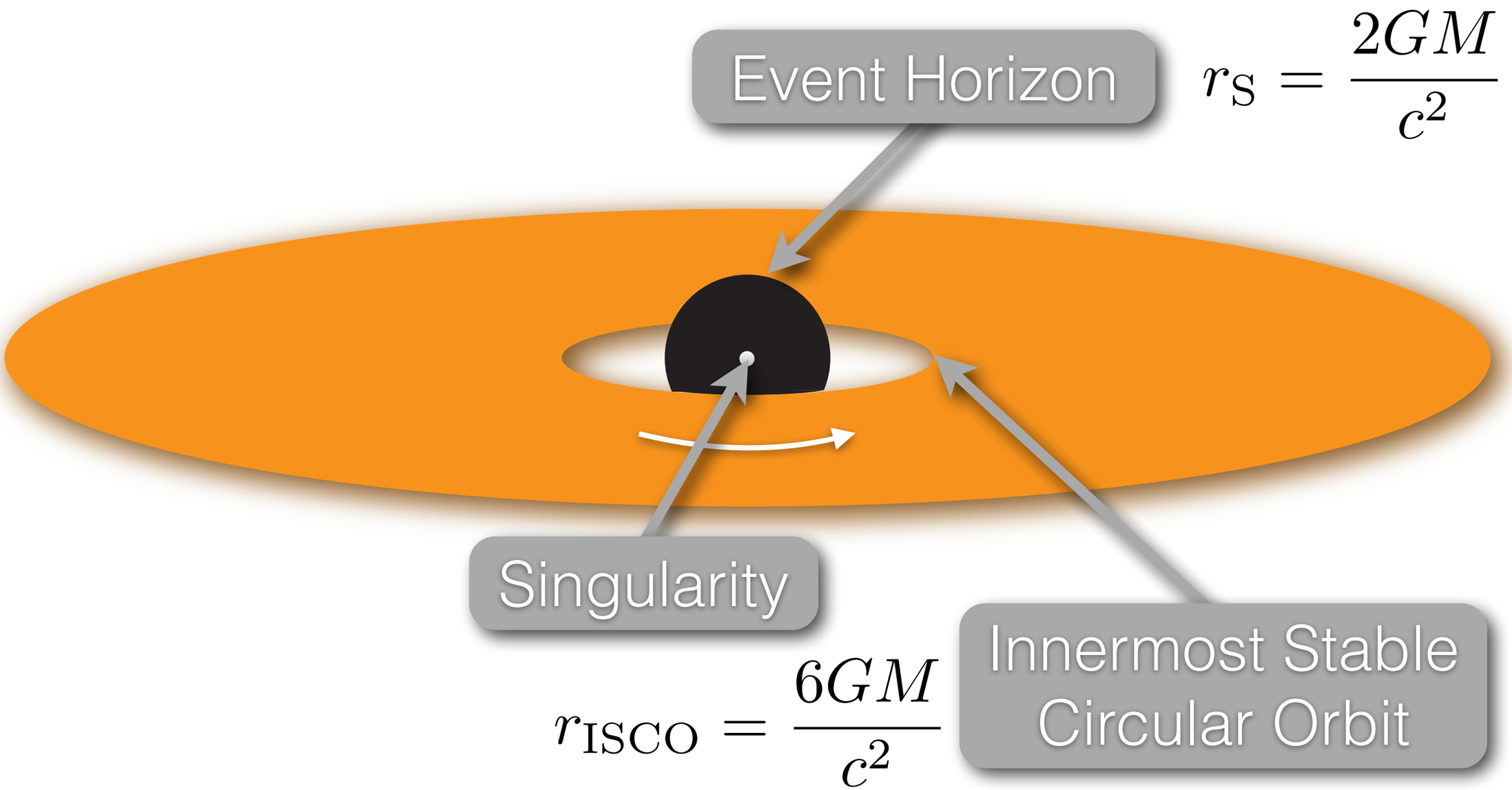
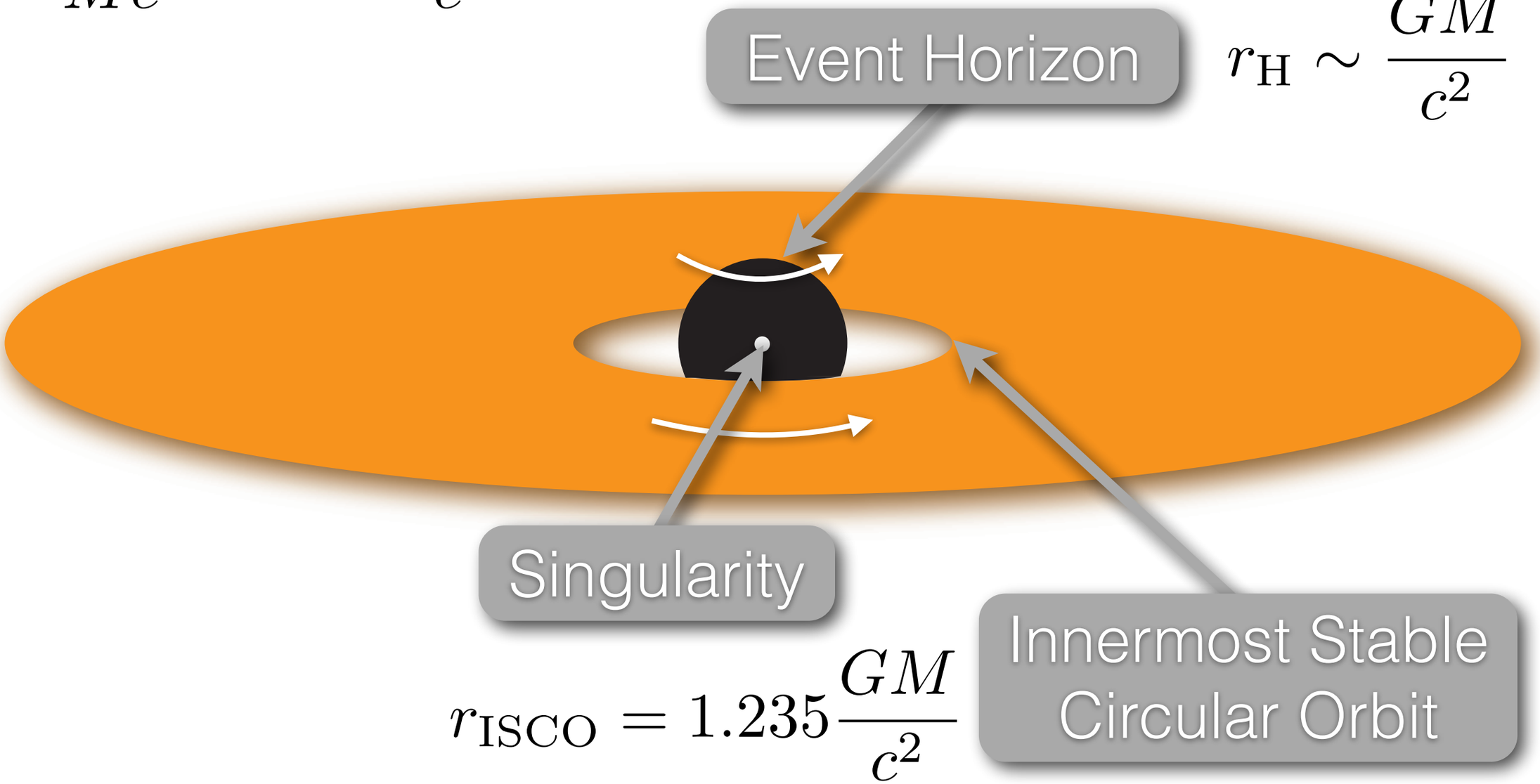
Anatomy of a Black Hole



Anatomy of a Black Hole

$$a = \frac{J}{Mc} = 0.998\frac{GM}{c^2}$$

$$r_{\rm H} \sim \frac{GM}{c^2}$$



$$r_{\rm ISCO} = 1.235\frac{GM}{c^2}$$

The No Hair Theorem

Black holes are entirely described by 3 properties

- Mass
- Spin
- Electrical Charge – but astrophysical black holes are probably uncharged

But the physics of the surrounding/accreting environment can be much more complicated

How do you power something so bright?

$$L = \epsilon \dot{M} c^2$$

Assume the radiation we see is from the gravitational potential lost between infinity and the innermost stable orbit

How do you power something so bright?

$$L = \epsilon \dot{M} c^2$$

Assume the radiation we see is from the gravitational potential lost between infinity and the innermost stable orbit

$$L = \frac{GM\dot{M}}{r} - \frac{1}{2}\dot{M}v^2 = \frac{GM\dot{M}}{2r}$$

$$\epsilon = \frac{L}{\dot{M}c^2} \qquad r = \frac{6GM}{c^2} \qquad \epsilon = \frac{1}{12}$$ Newtonian Gravity

$$\epsilon = 0.057$$ full GR, no rotation

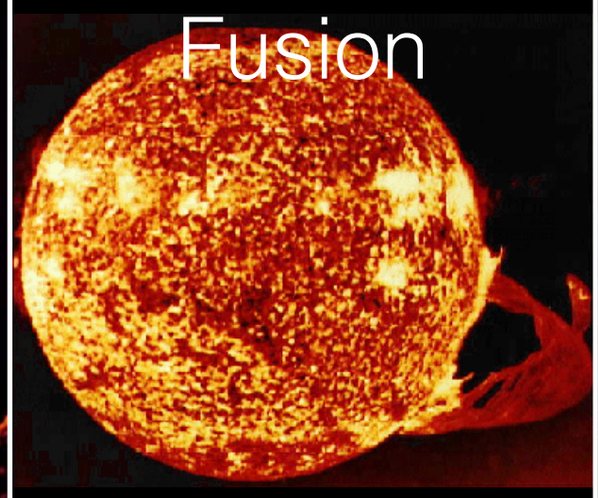
$$\epsilon = 0.4$$ GR, maximally rotating

How does it compare?

$$L = \epsilon \dot{M} c^2$$

How does it compare?

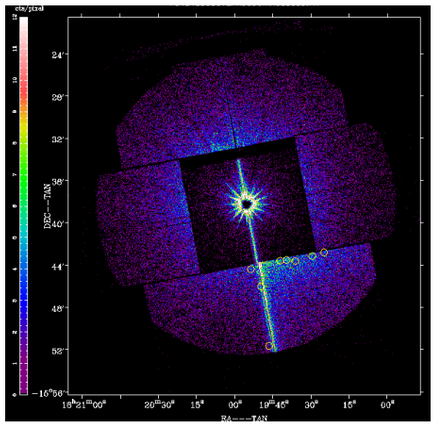
$$L = \epsilon \dot{M} c^2$$

Chemistry	Nuclear Fission	Nuclear Fusion	Accretion
			
$\varepsilon = 10^{-7}$	$\varepsilon = 10^{-4}$	$\varepsilon = 10^{-3}$	$\varepsilon \sim 0.4$

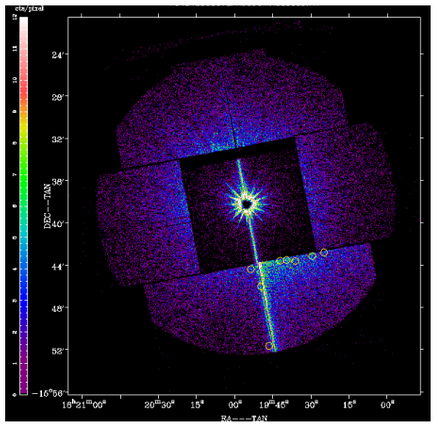
How do we know it's a black hole?

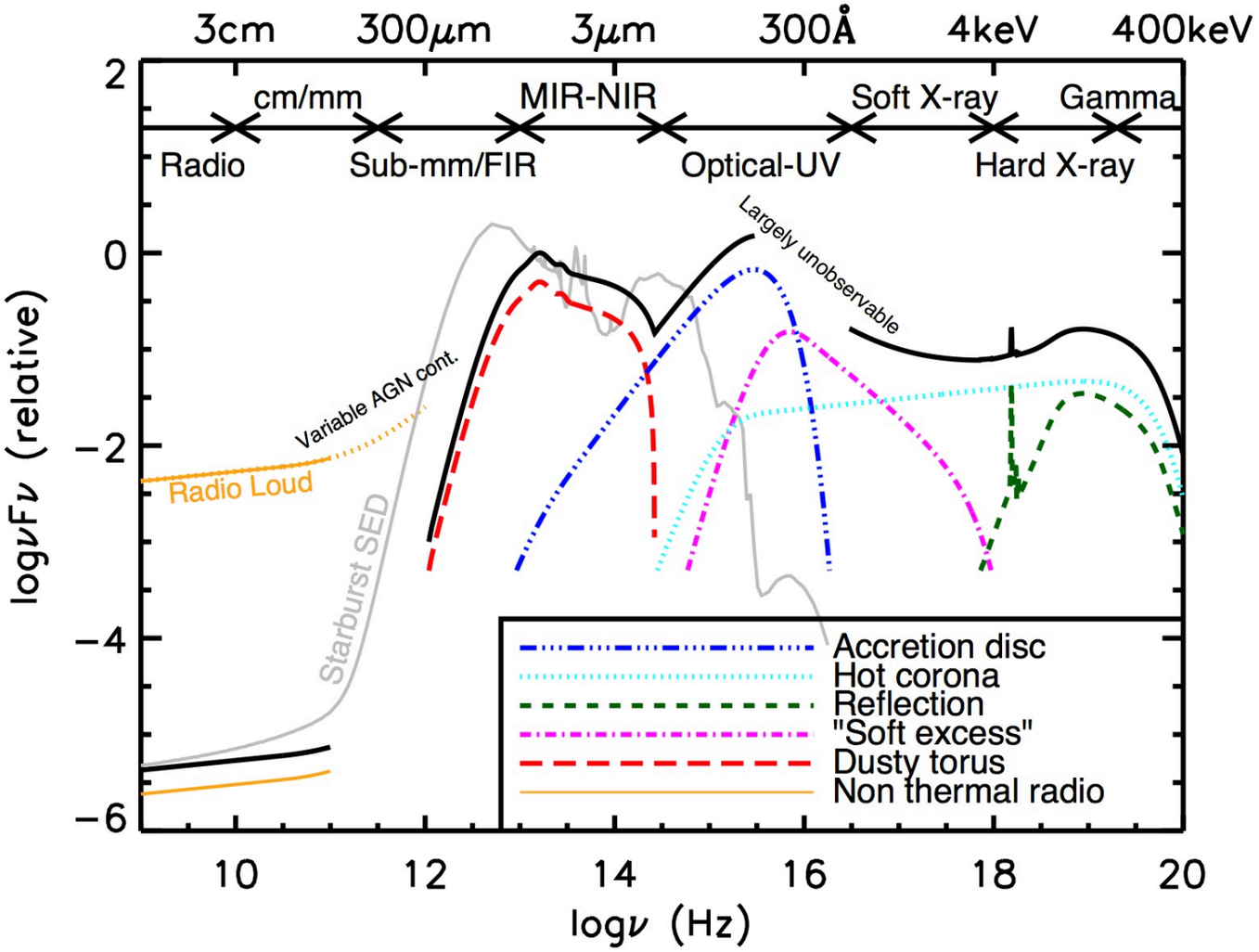
- Luminosity – need a sufficient mass accretion rate falling deep enough into gravitational potential
- Mass – in a black hole binary or in Galactic centre, force on stars
- Compactness
  - Needs to fit within the accretion disc and within orbits of stars
  - Variability timescale, to vary on timescale τ, must be able to carry information across it on that timescale, limiting size to $c\tau$
- The mass must lie within the event horizon predicted by General Relativity, so must be a black hole

Black Holes in AGN – What Do We See?



Black Holes in AGN – What Do We See?





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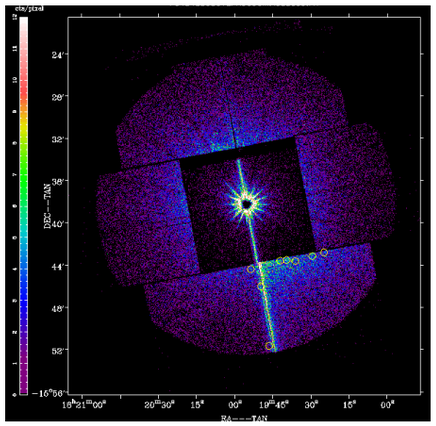

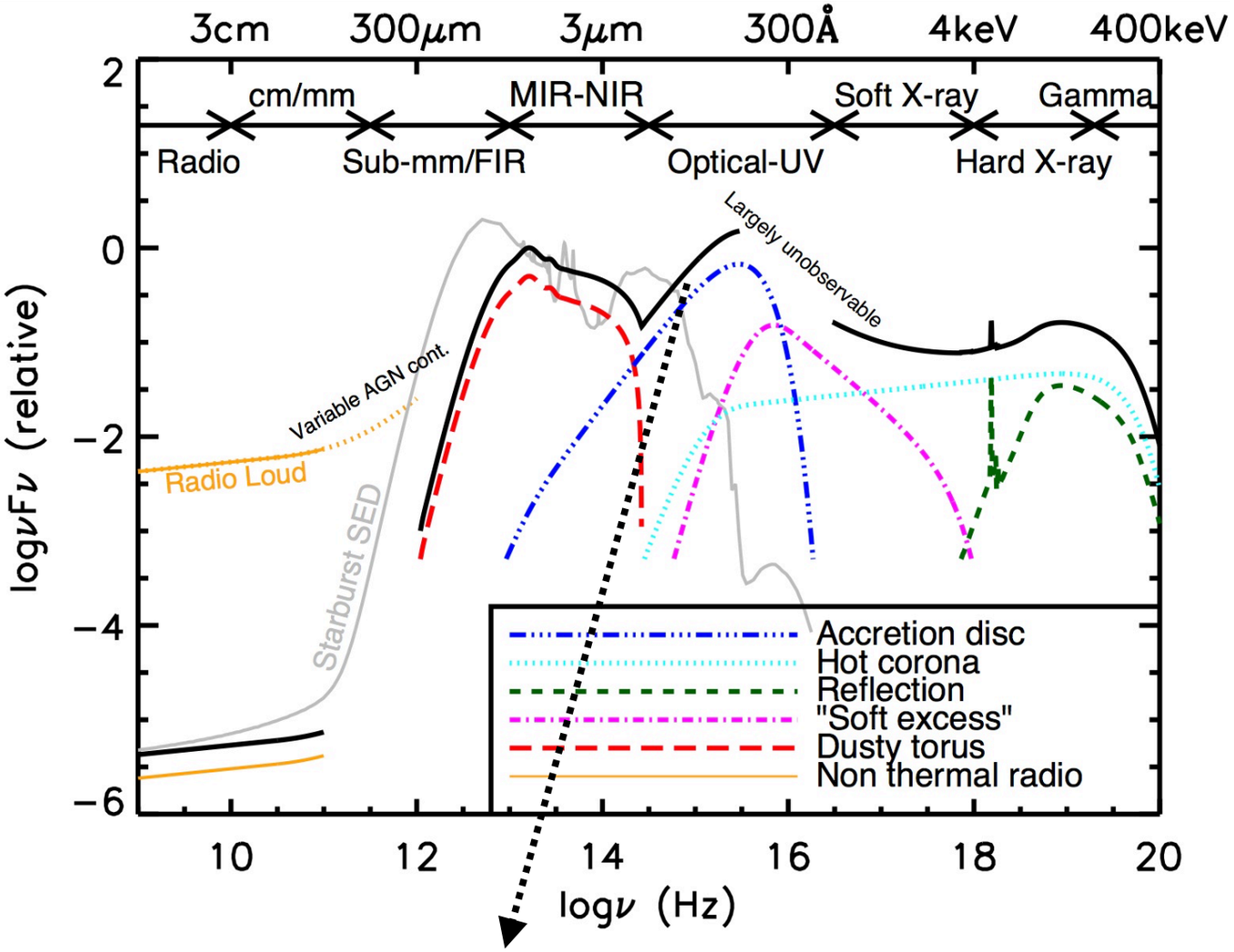

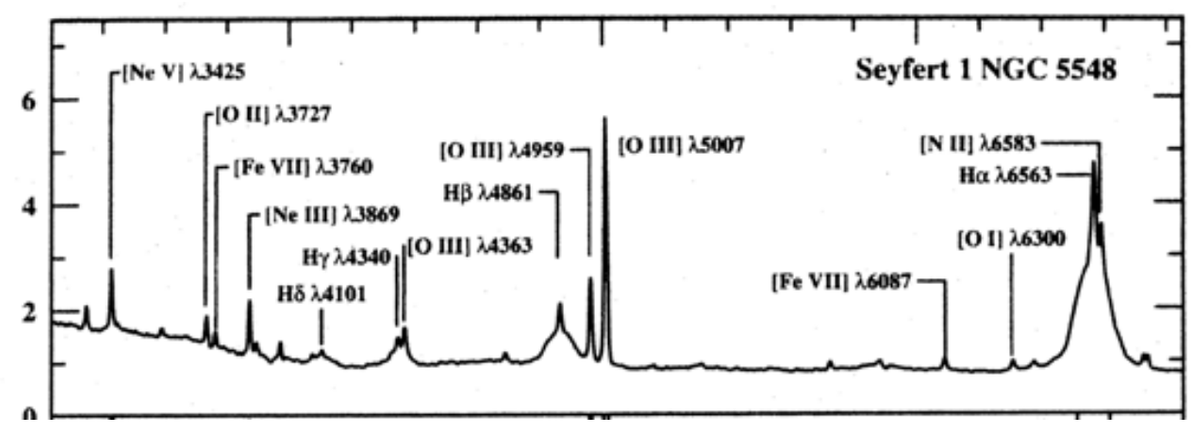

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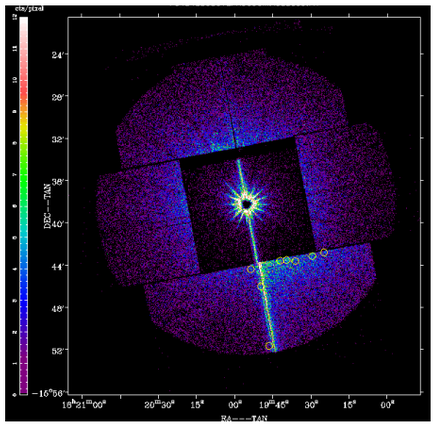
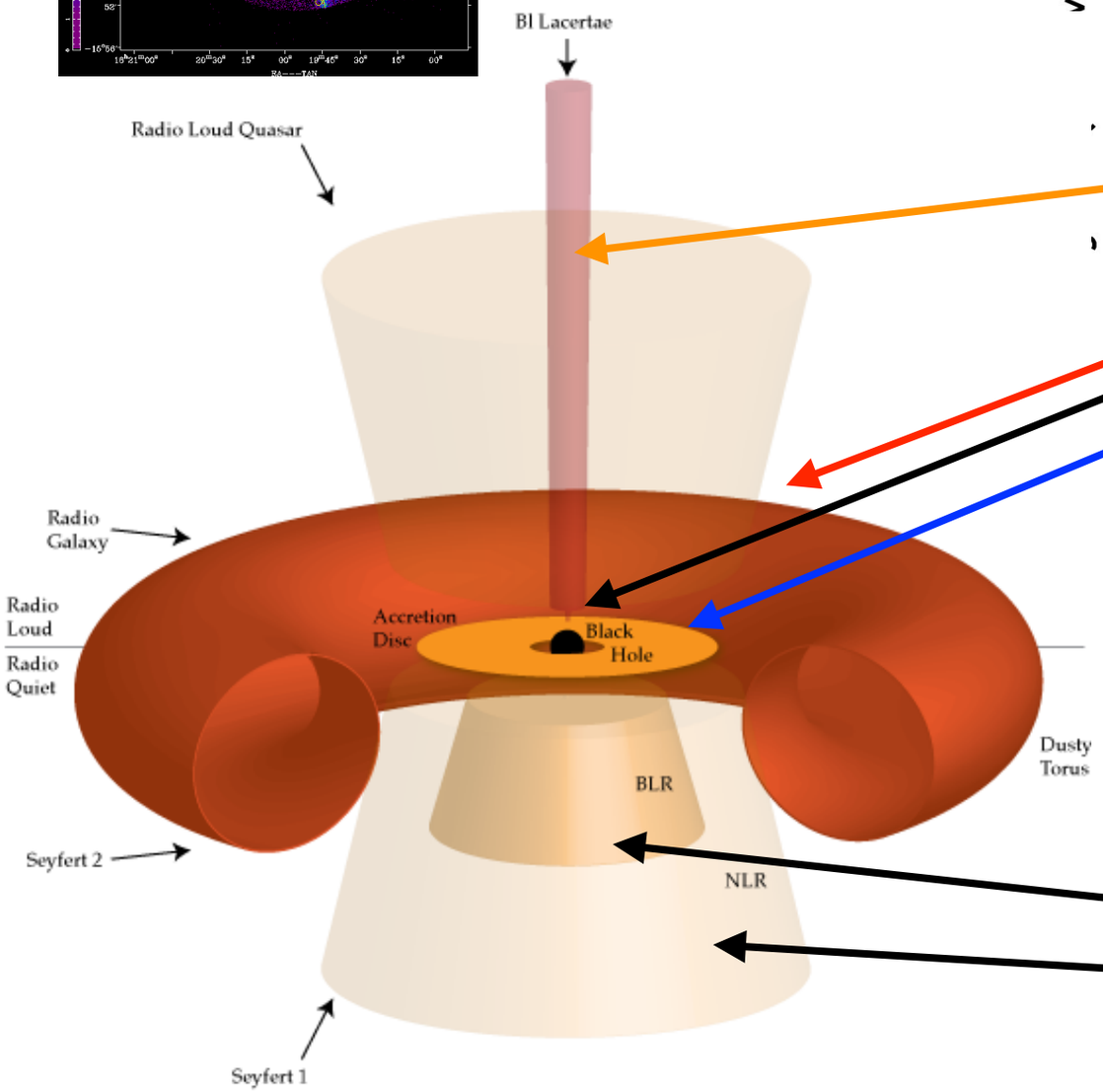
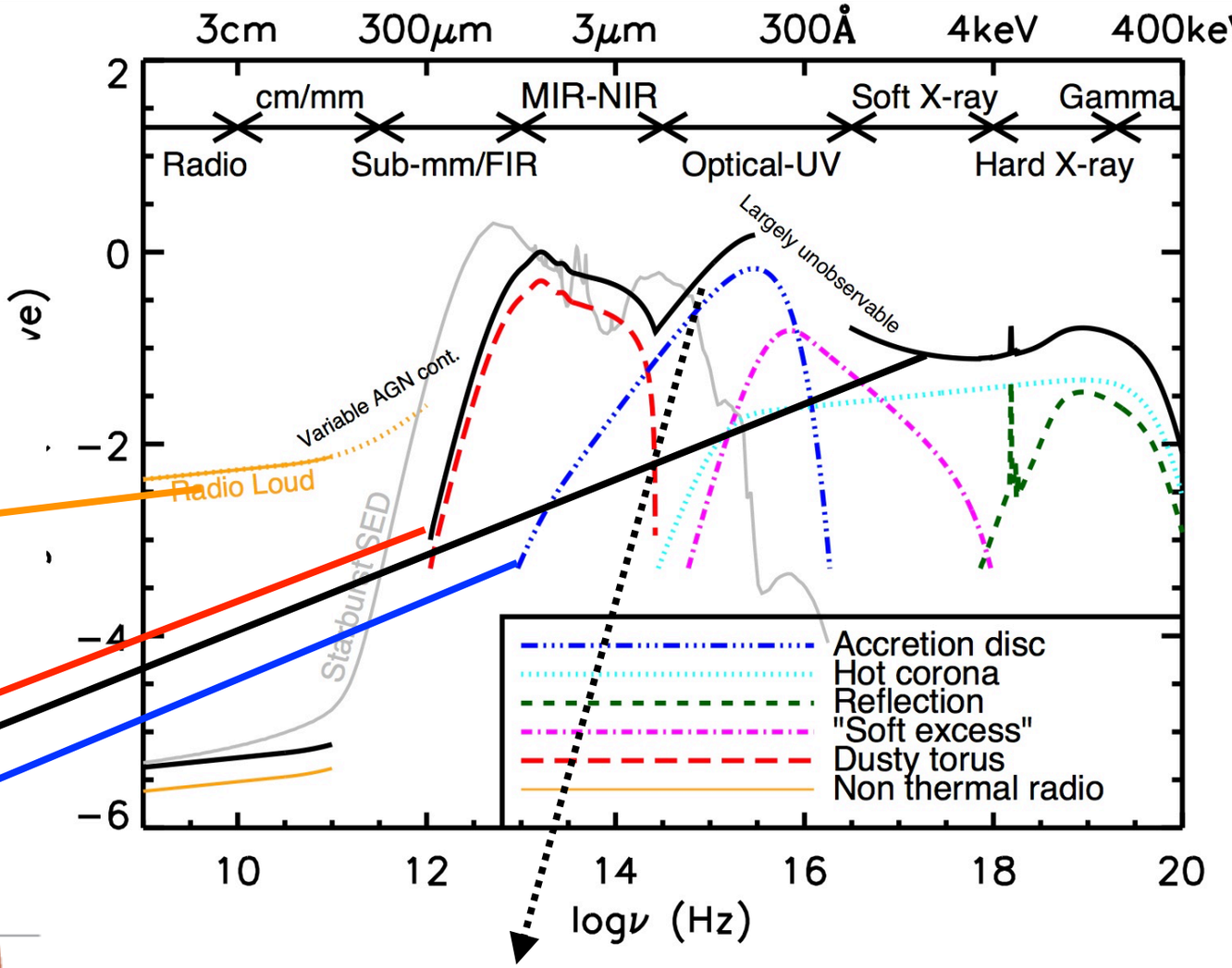
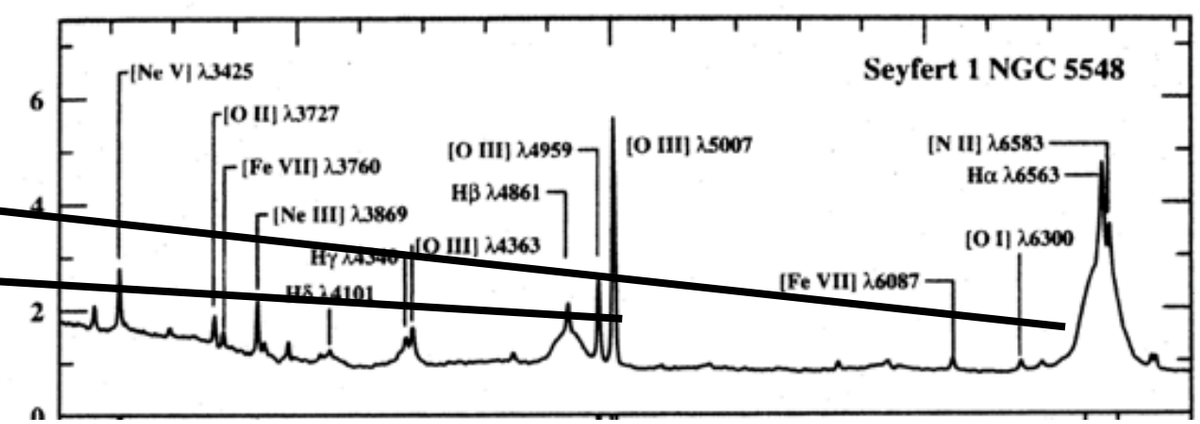


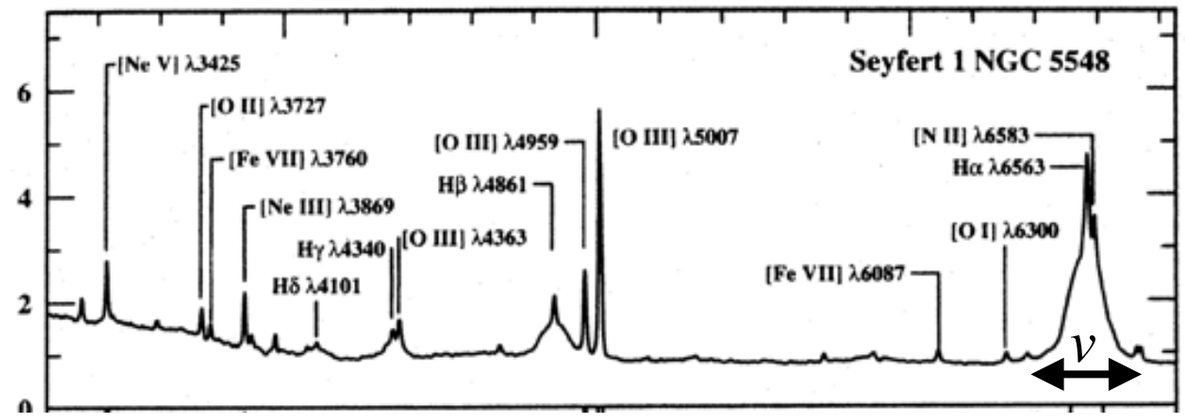


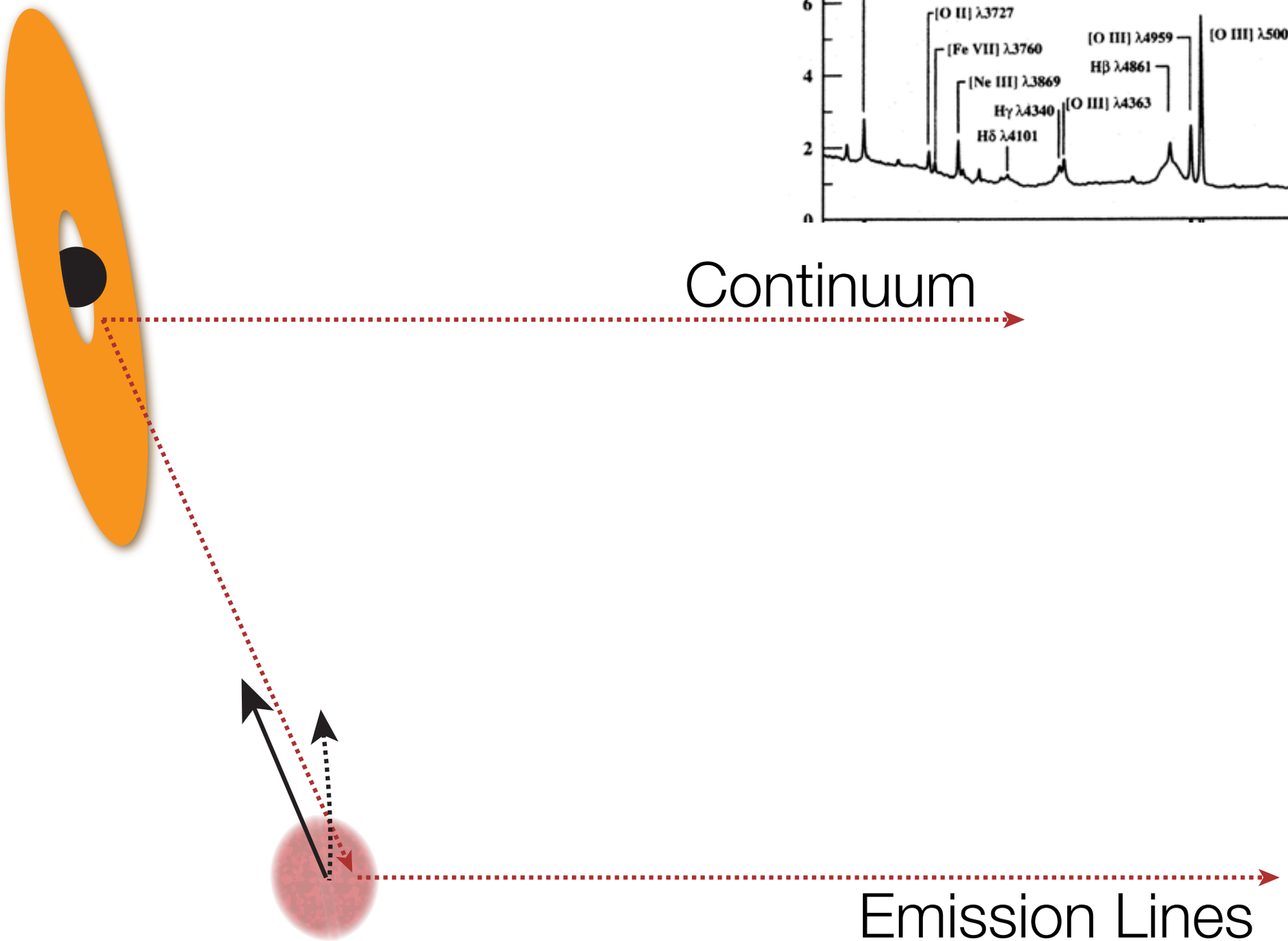




Measuring the Mass

Optical Reverberation Mapping





Measuring the Mass

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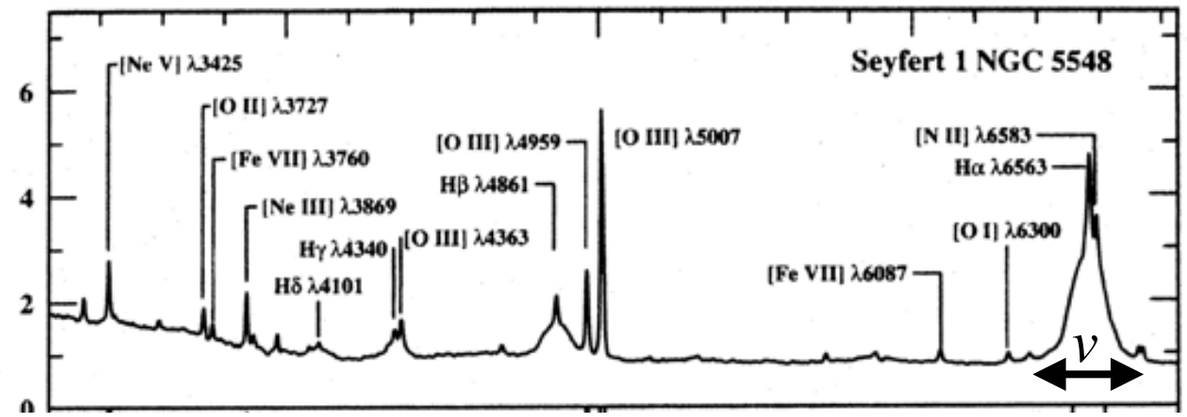
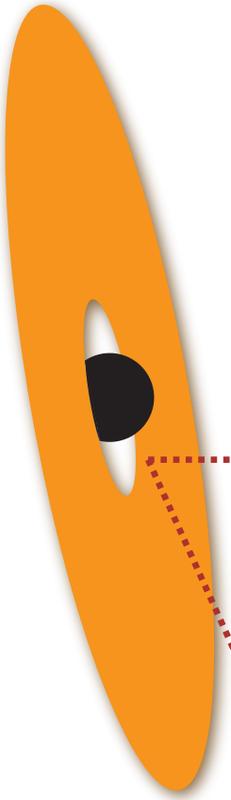
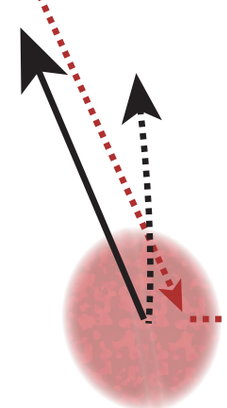




Continuum

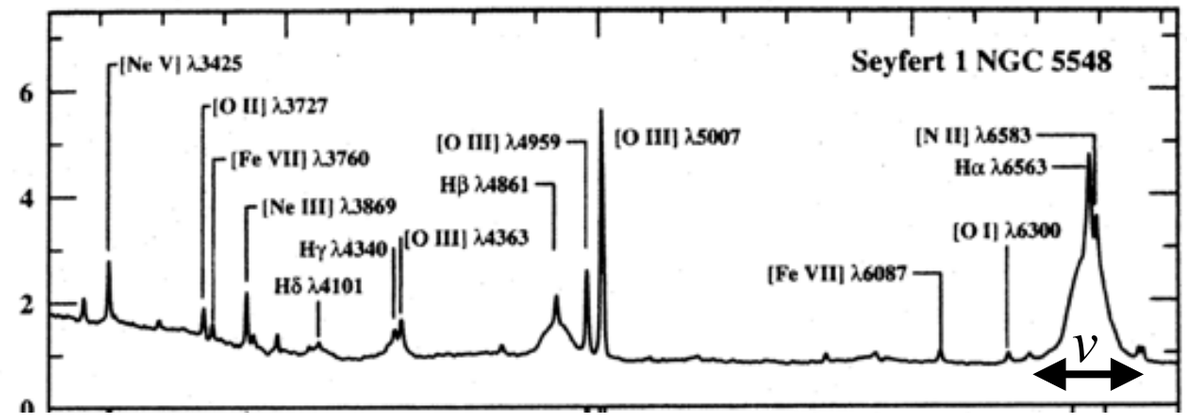
$$r = c\,\Delta t$$

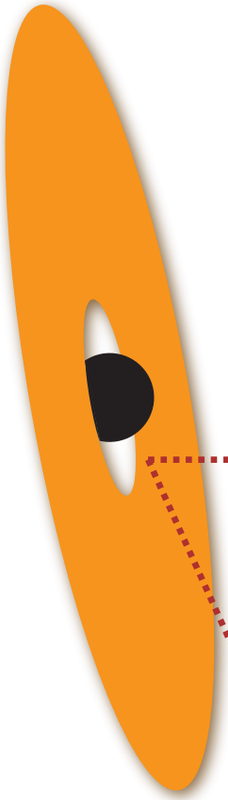


Emission Lines

Measuring the Mass

Optical Reverberation Mapping





Continuum

$$r = c\,\Delta t$$

$$\frac{mv^2}{r} = \frac{GM_{\rm BH}m}{r^2}$$

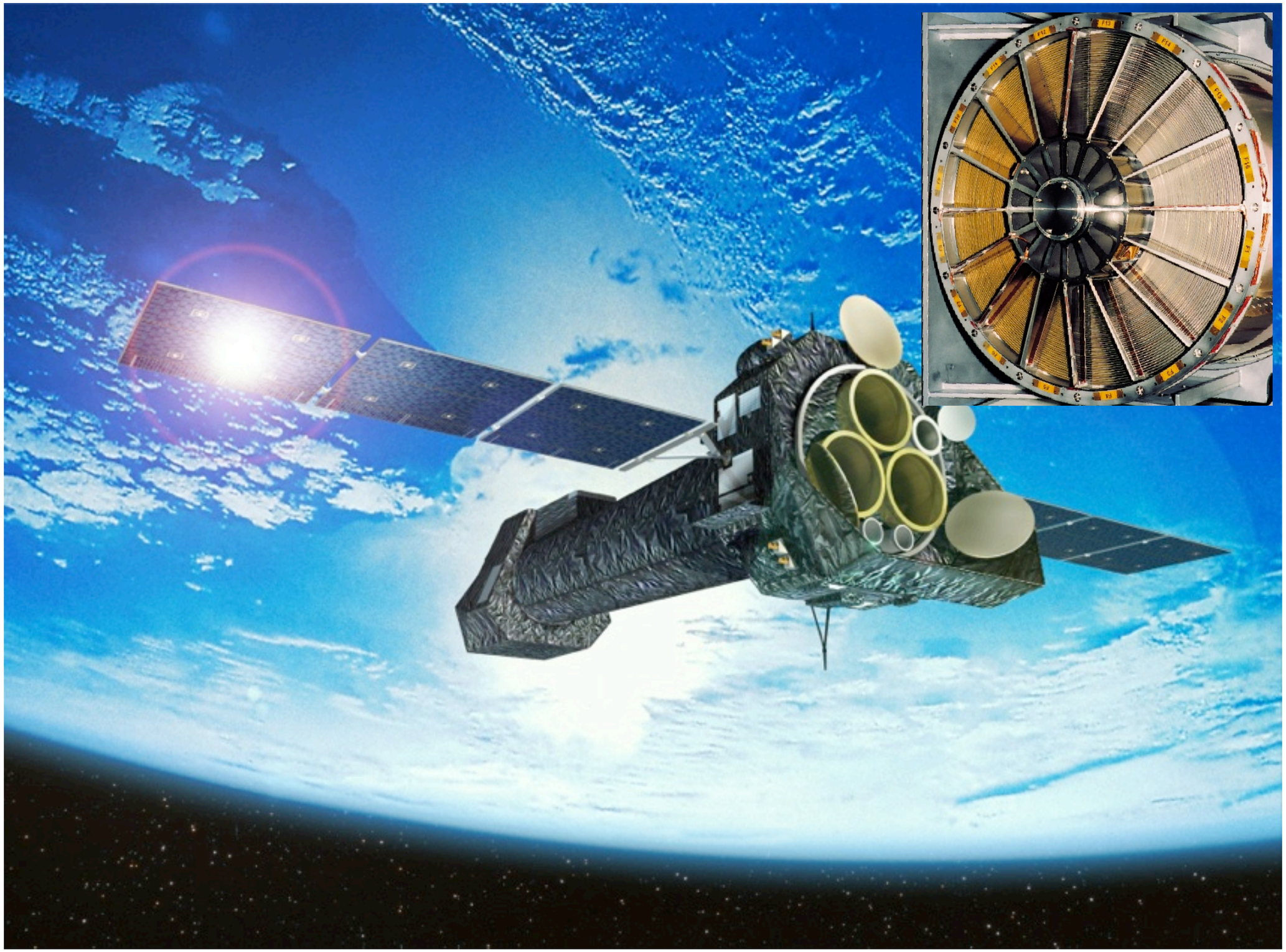
Emission Lines

X-ray Telescopes

XMM-Newton

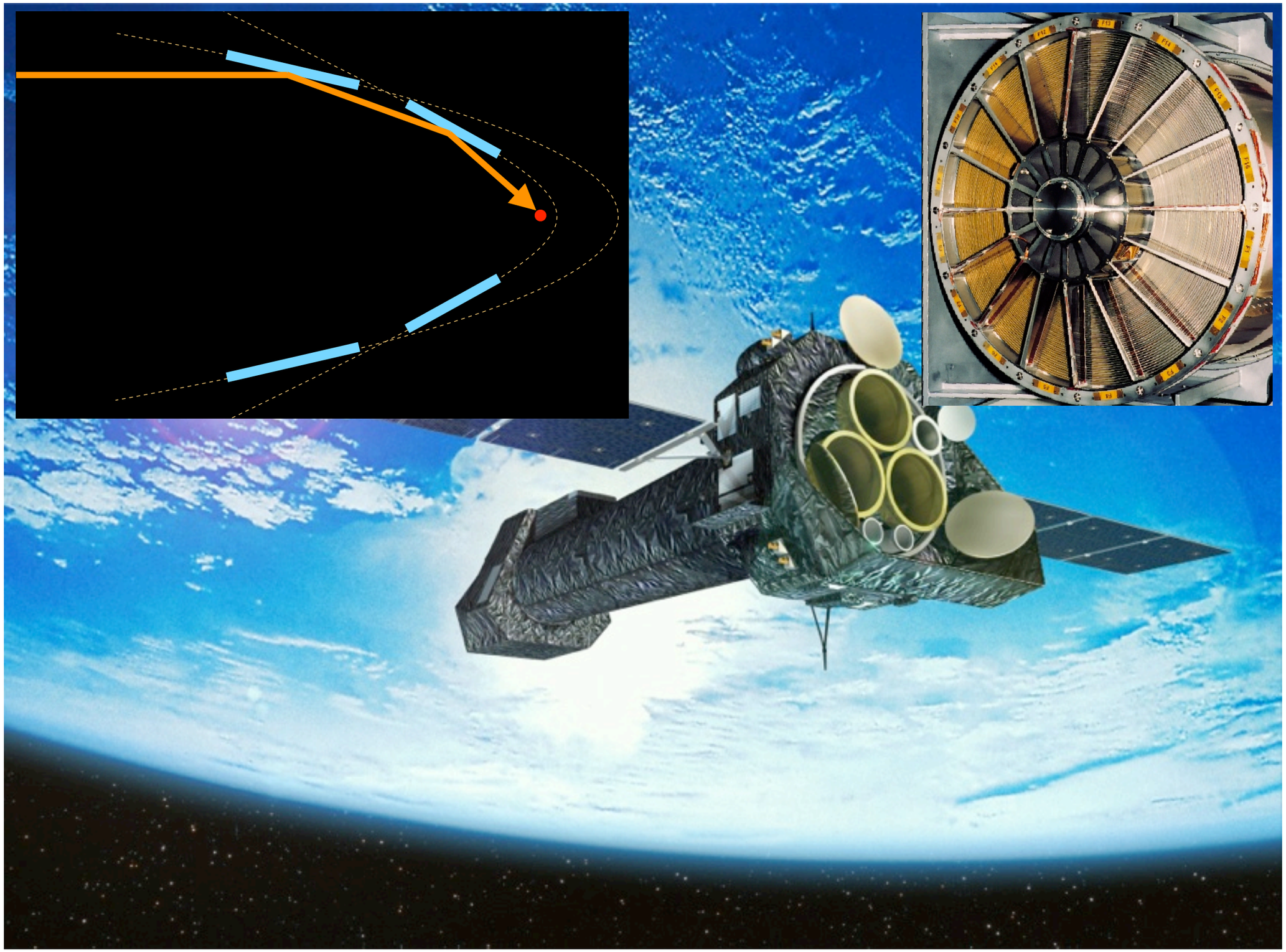
X-ray Telescopes

XMM-Newton



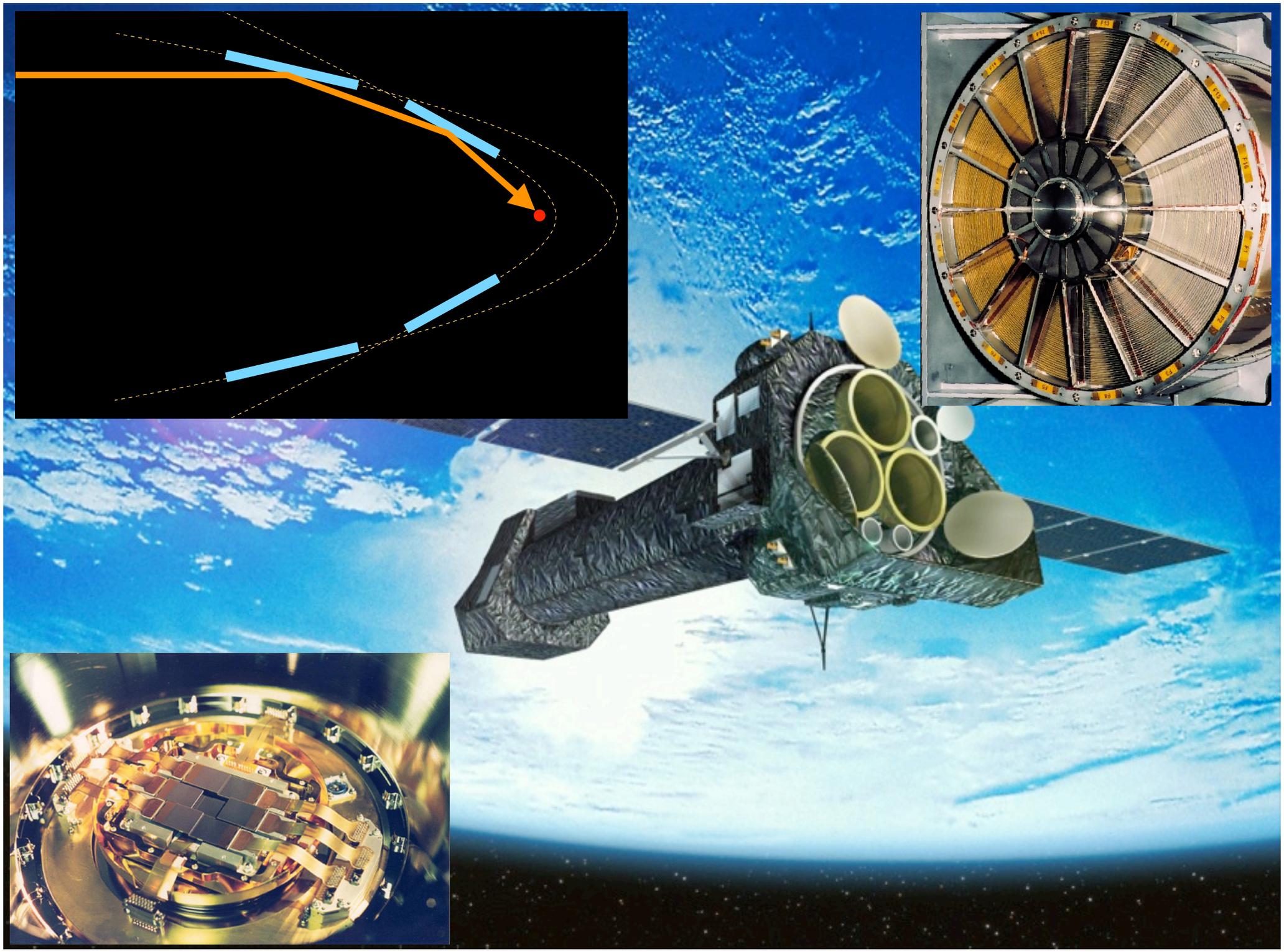
X-ray Telescopes

XMM-Newton



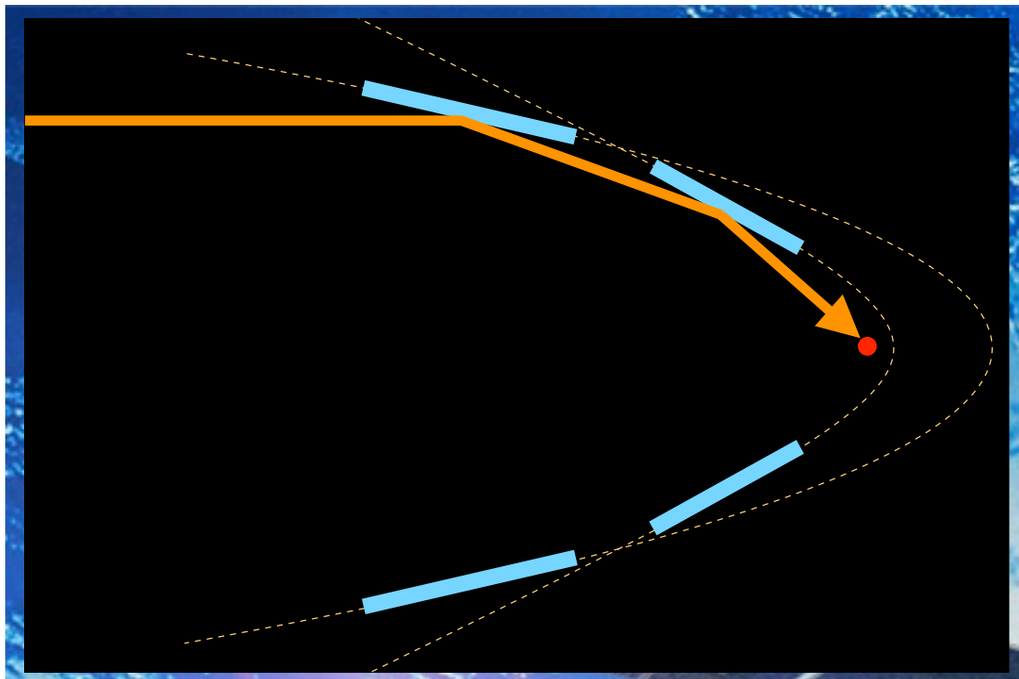
X-ray Telescopes

XMM-Newton



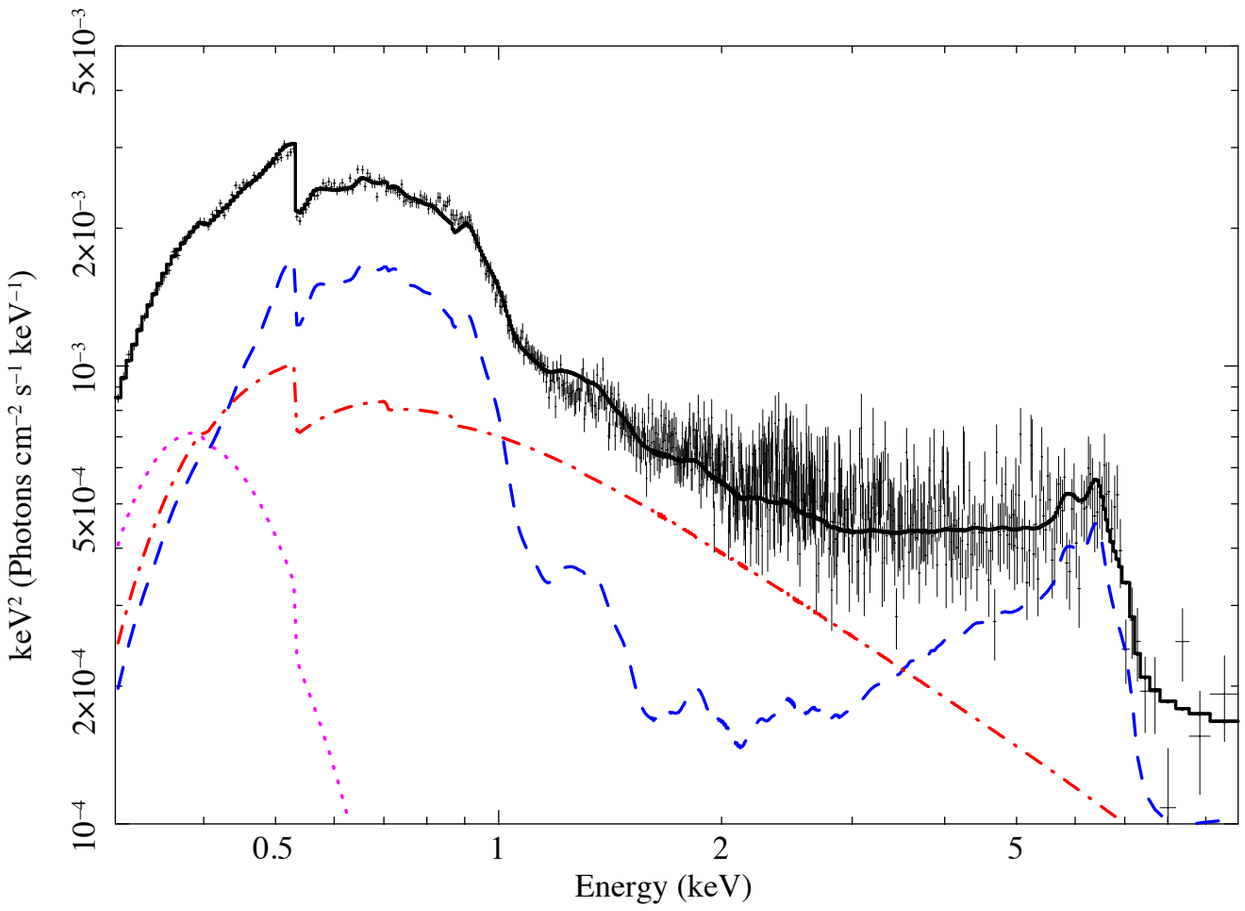
X-ray Telescopes

XMM-Newton

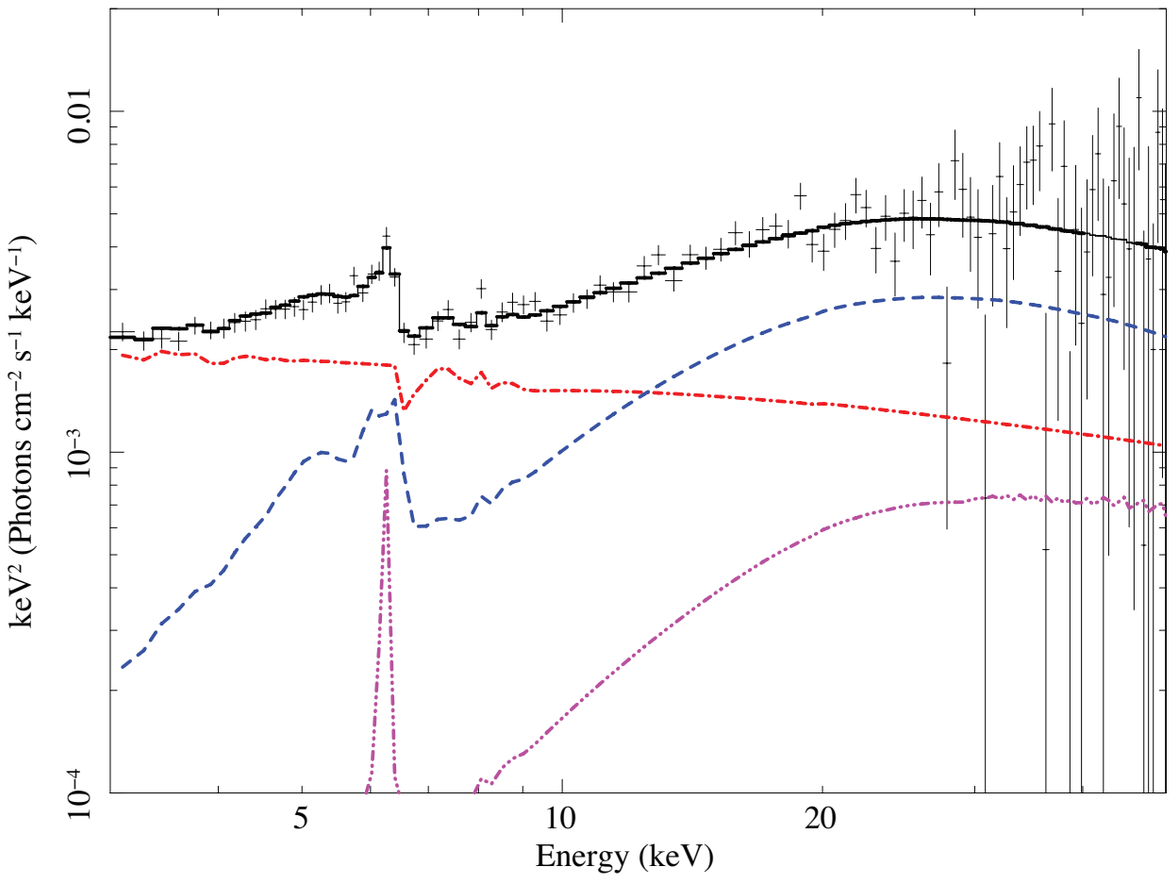


The X-ray Spectrum of an AGN

XMM-Newton



NuSTAR



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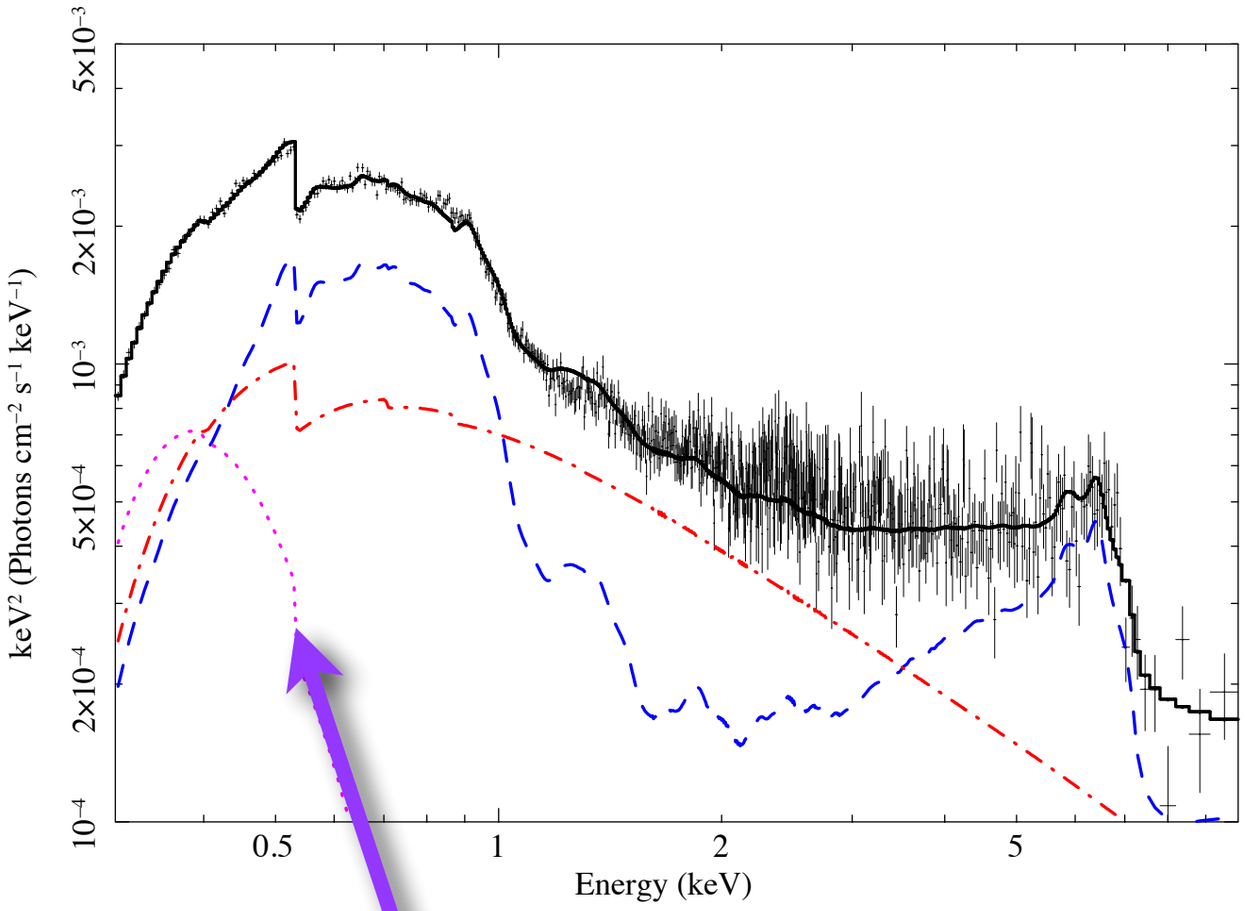
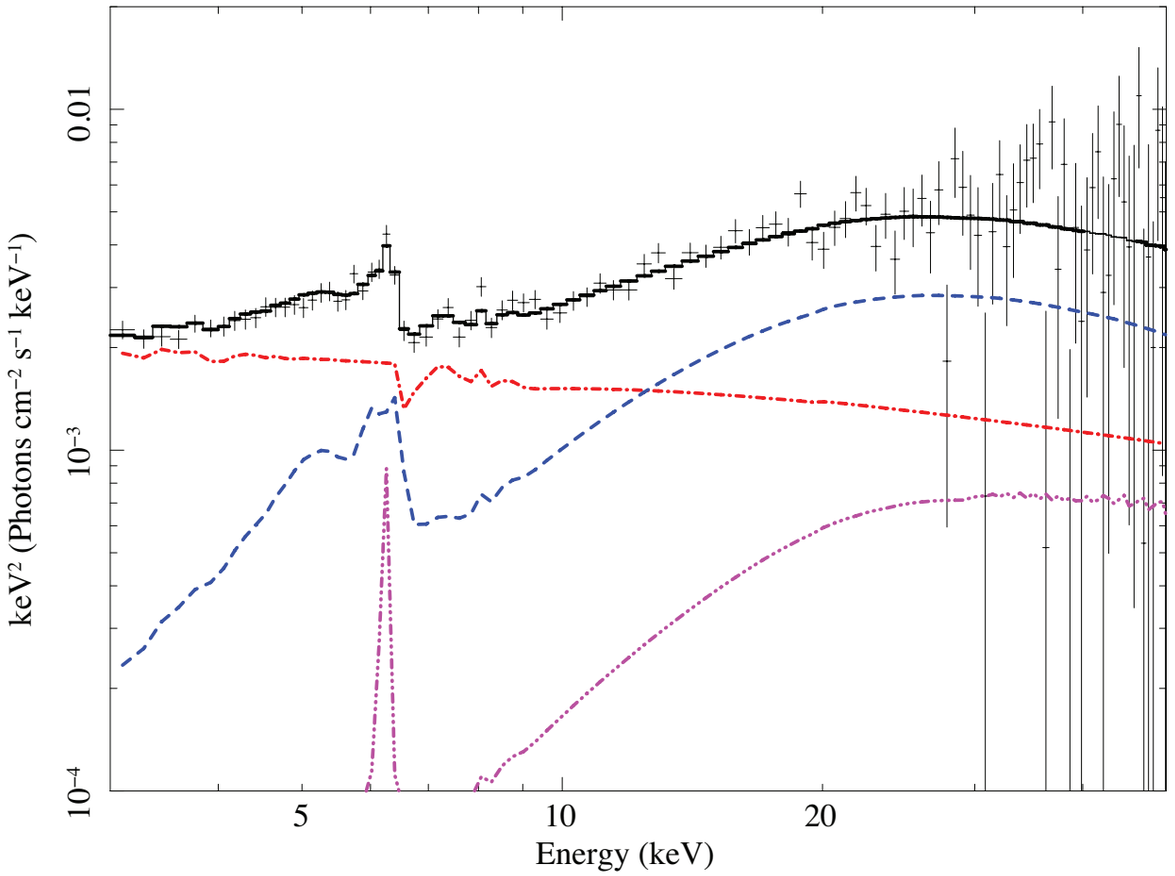


Thermal Emission (Accretion Disc)

NuSTAR



The X-ray Spectrum of an AGN

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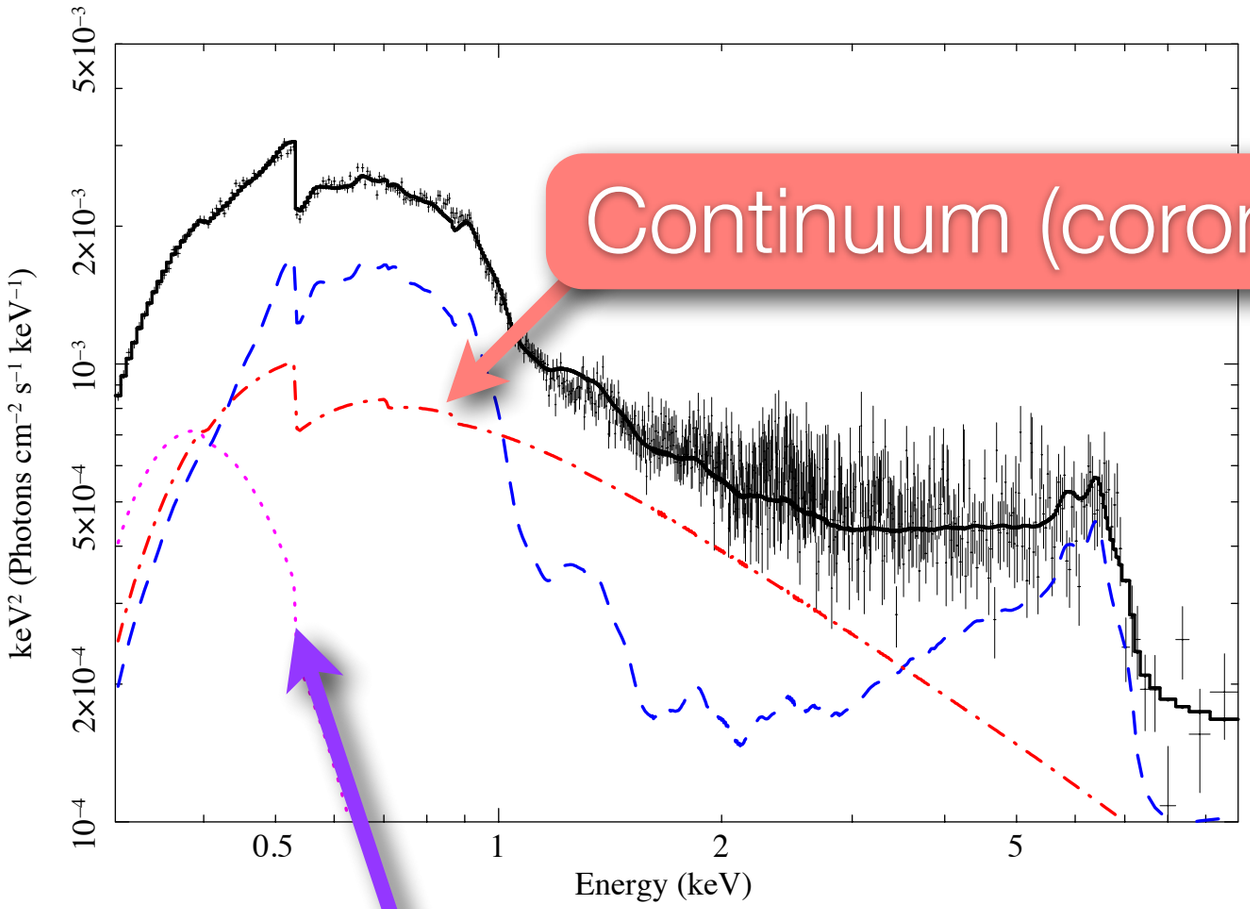

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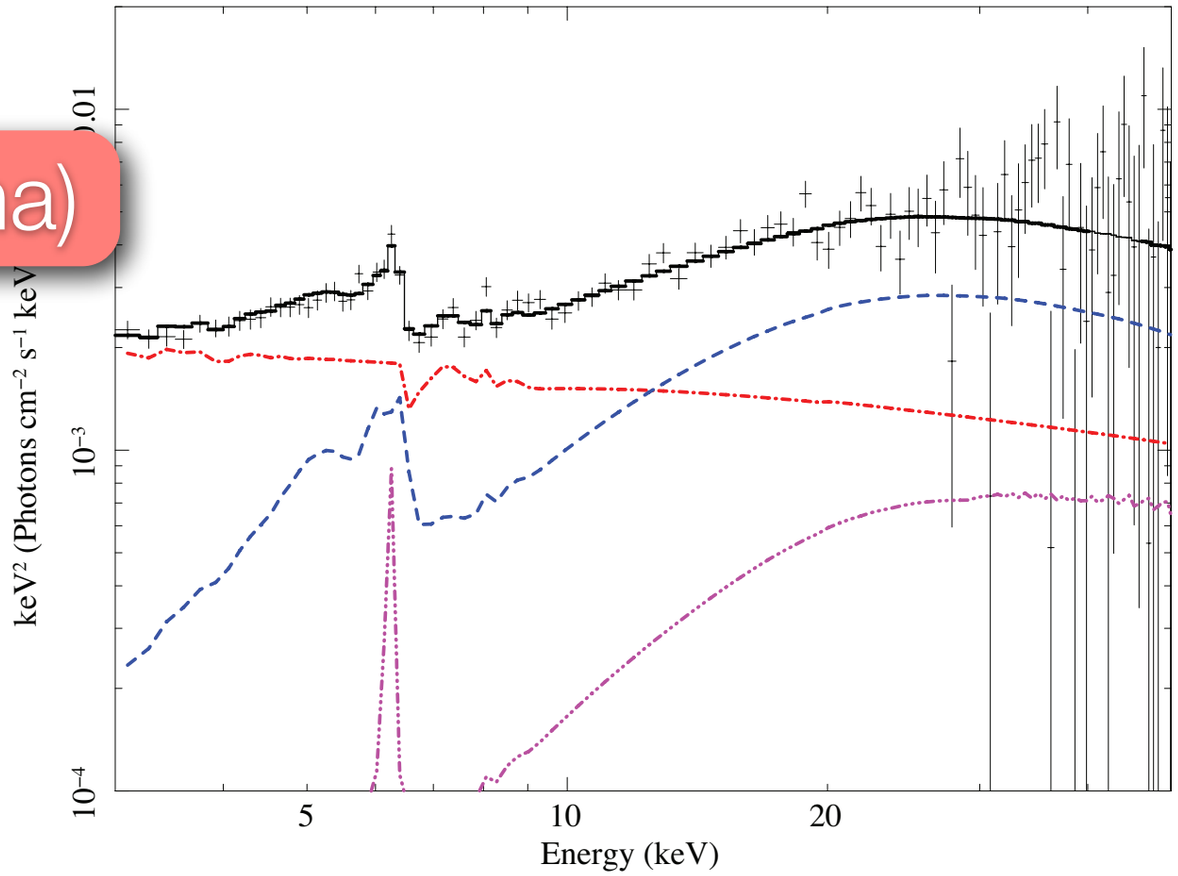


The X-ray Spectrum of an AGN

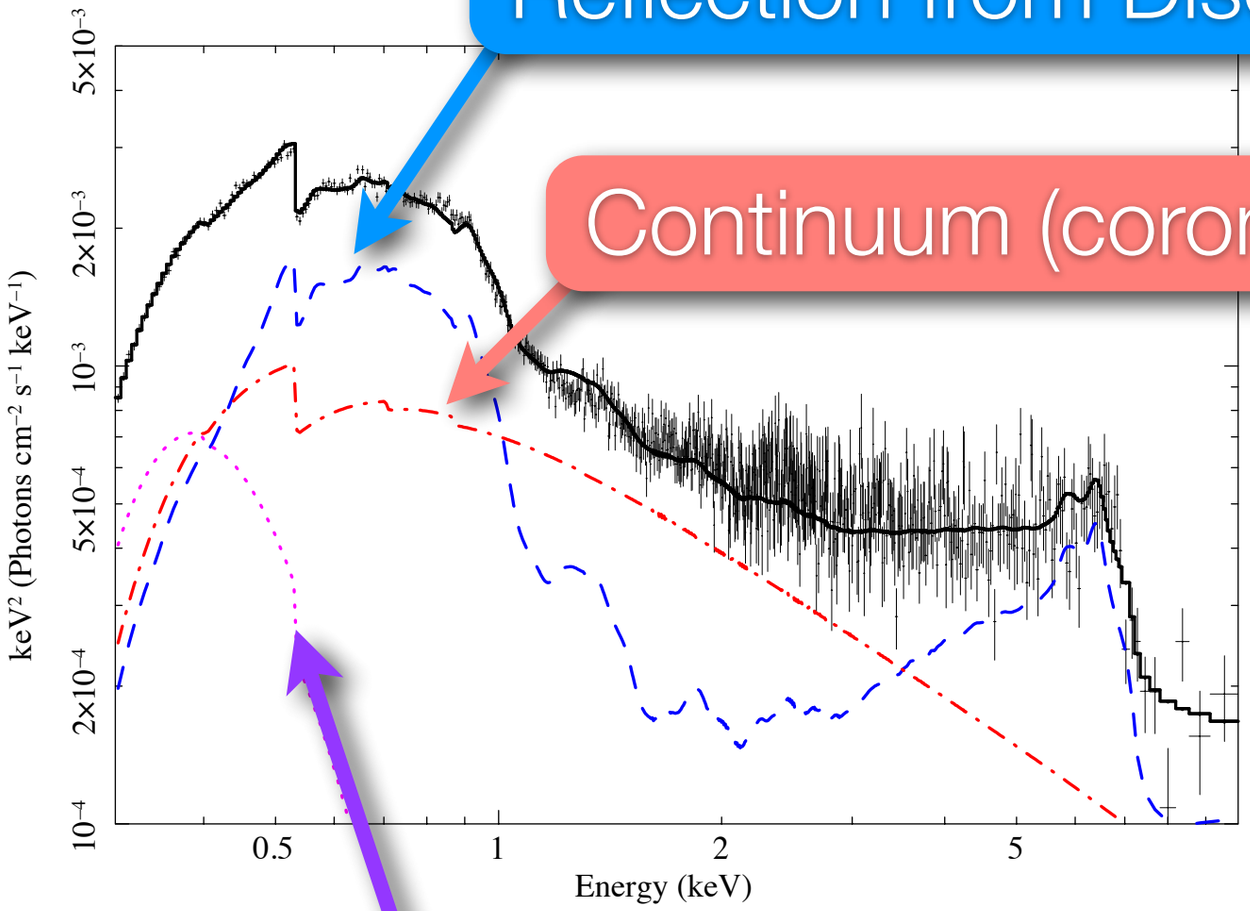
XMM-Newton

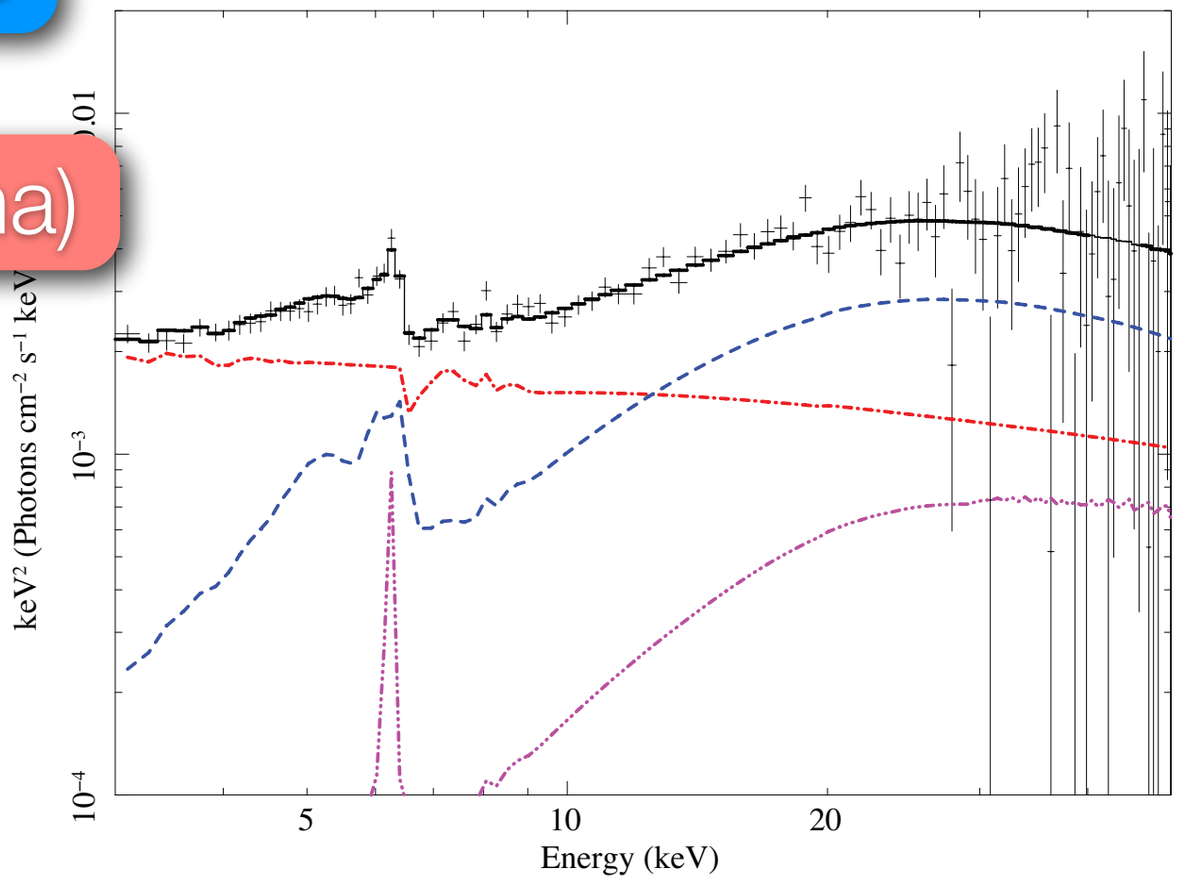
NuSTAR

Reflection from Disc

Continuum (corona)

Thermal Emission (Accretion Disc)





The X-ray Spectrum of an AGN

XMM-Newton

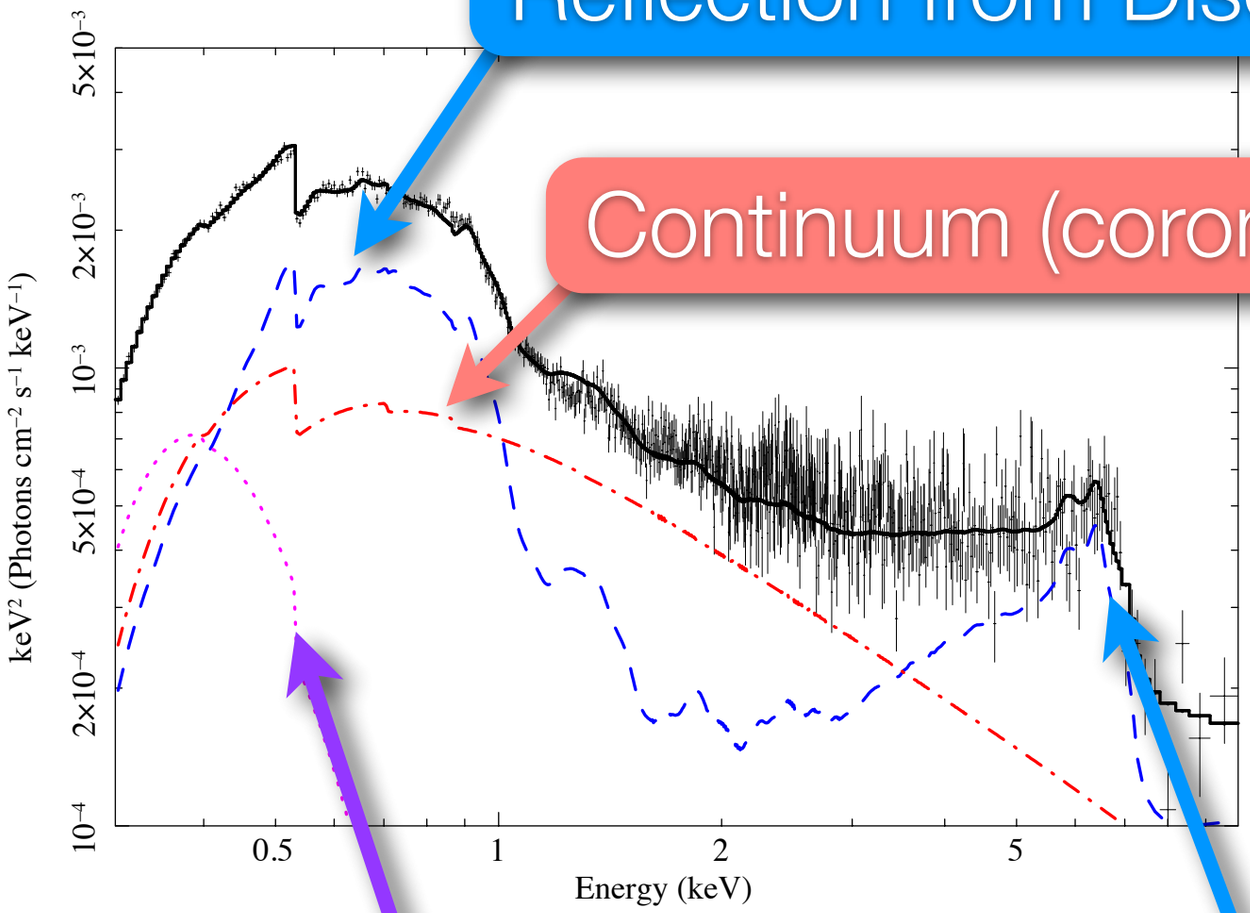
NuSTAR

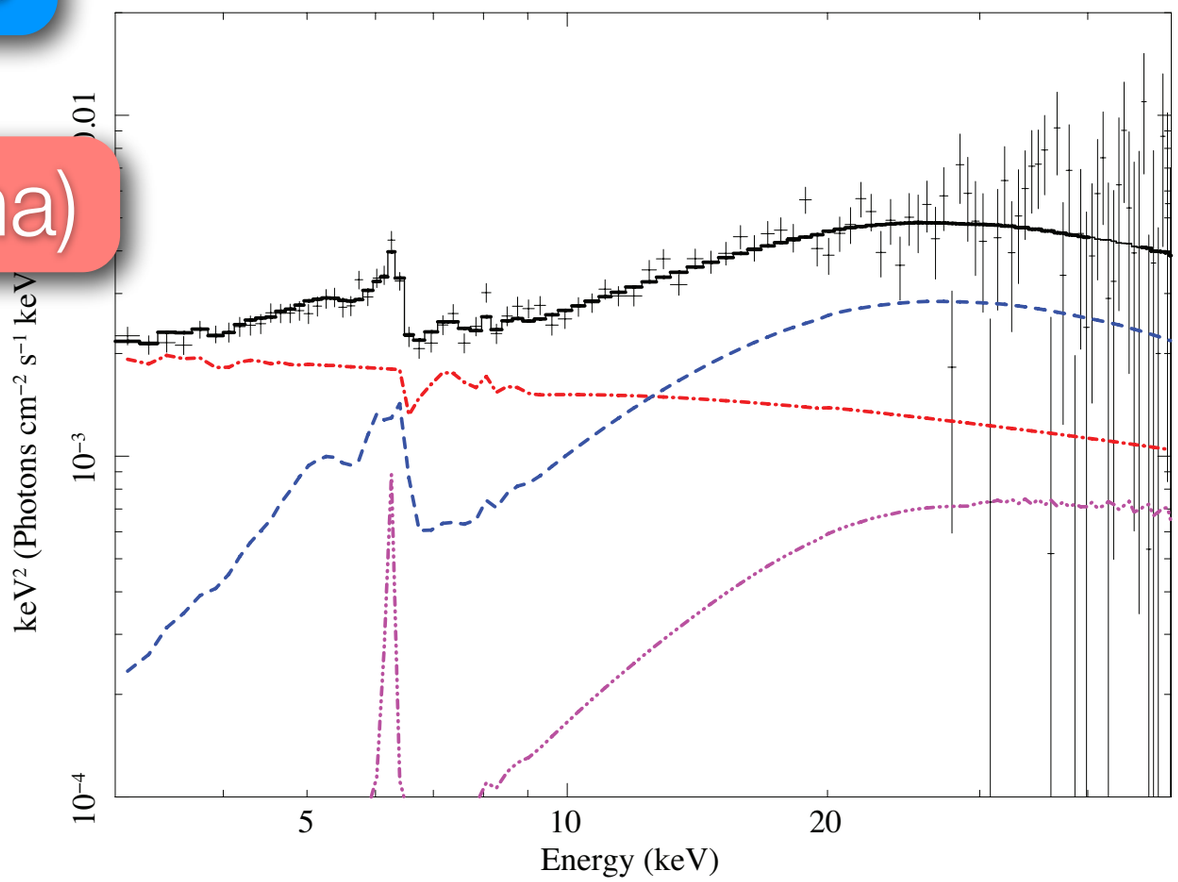
Reflection from Disc

Continuum (corona)

Thermal Emission (Accretion Disc)

Iron Kα Line





The X-ray Spectrum of an AGN

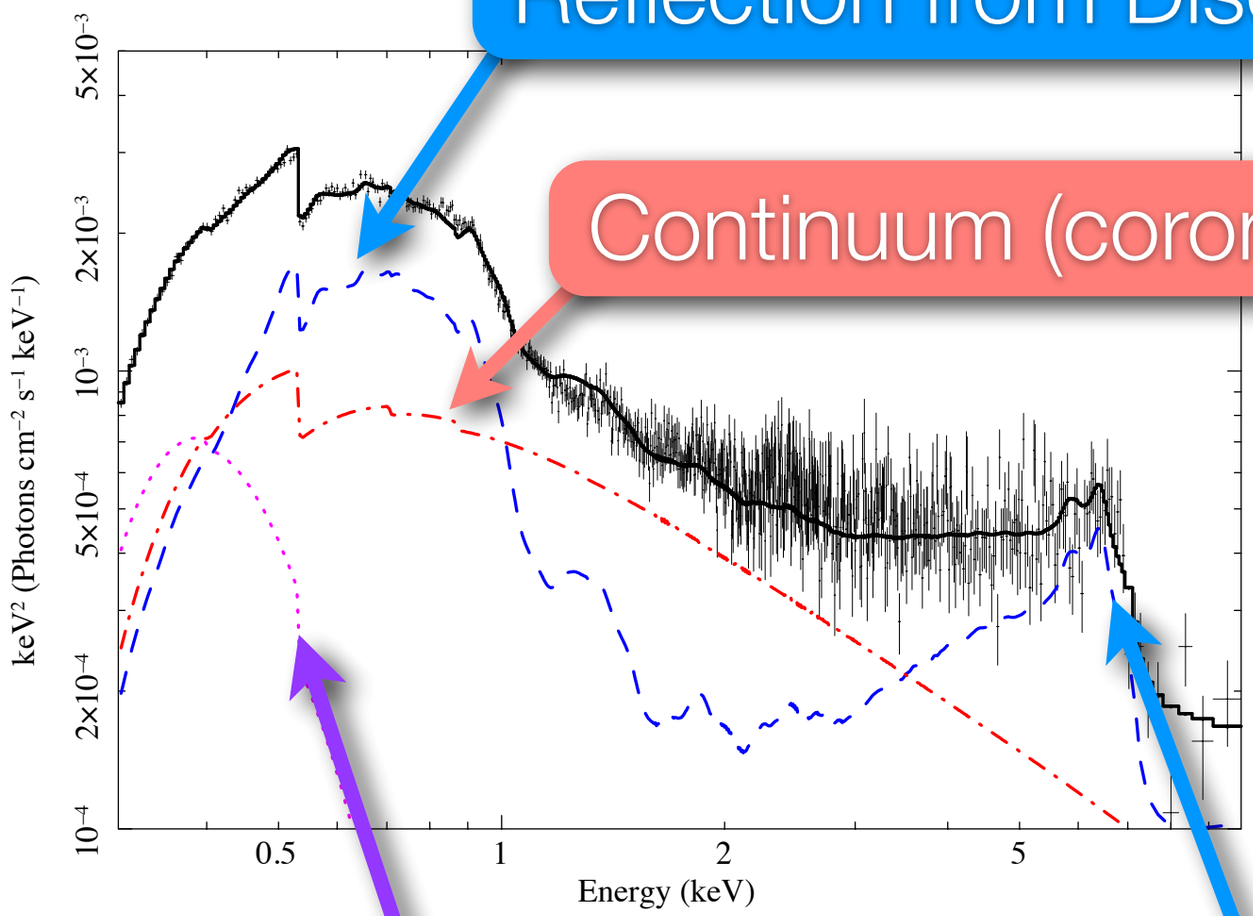
XMM-Newton

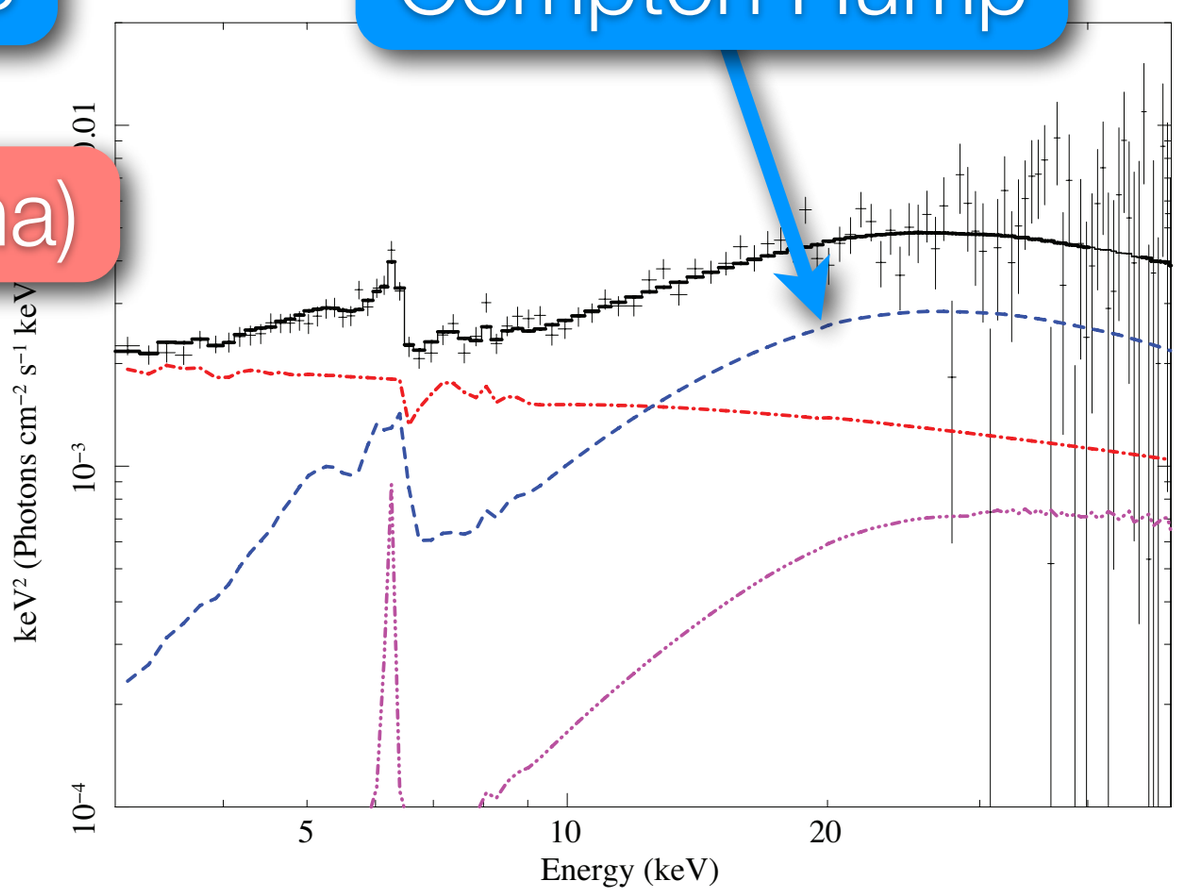
NuSTAR

Reflection from Disc

Compton Hump

Continuum (corona)

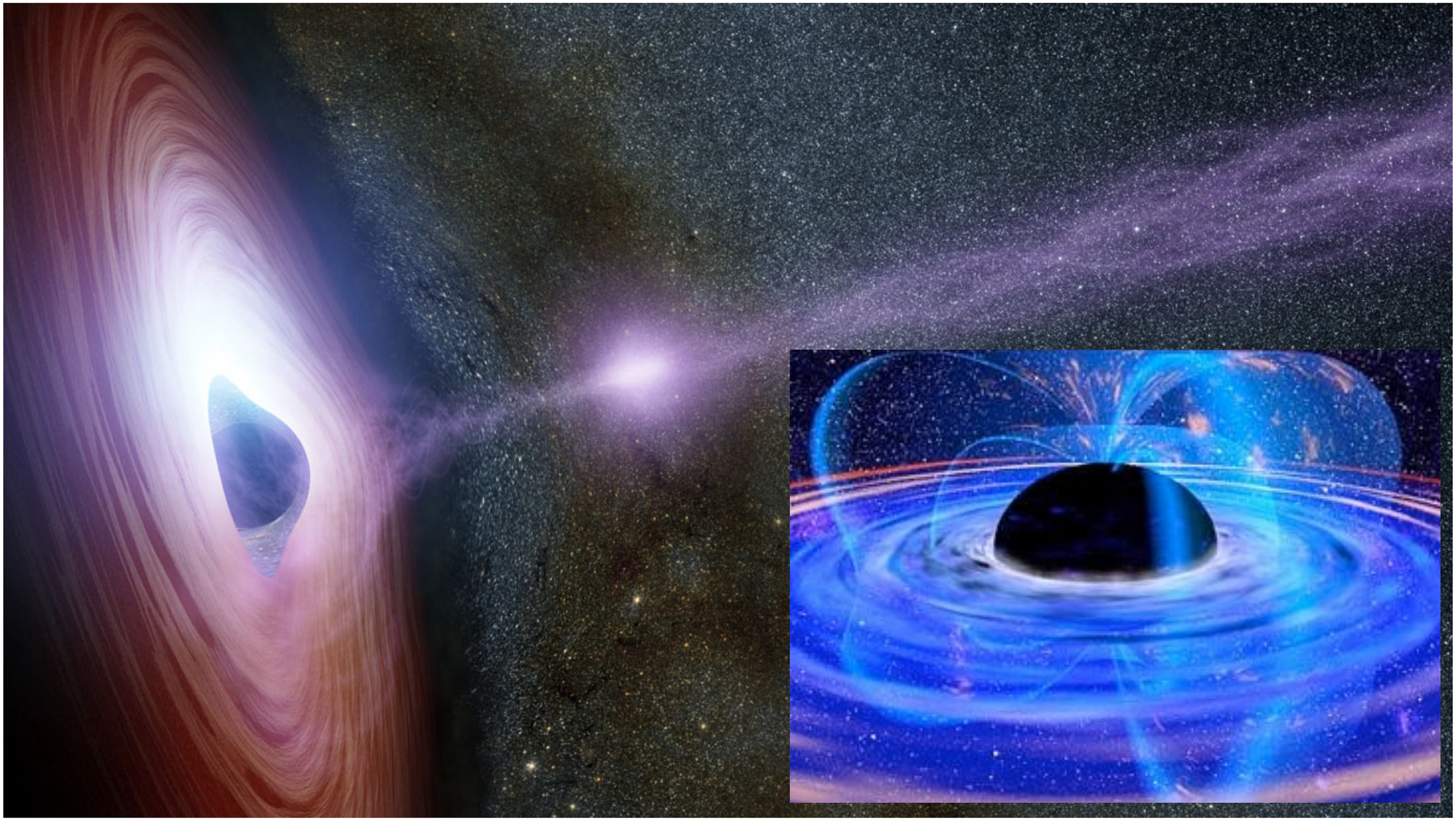




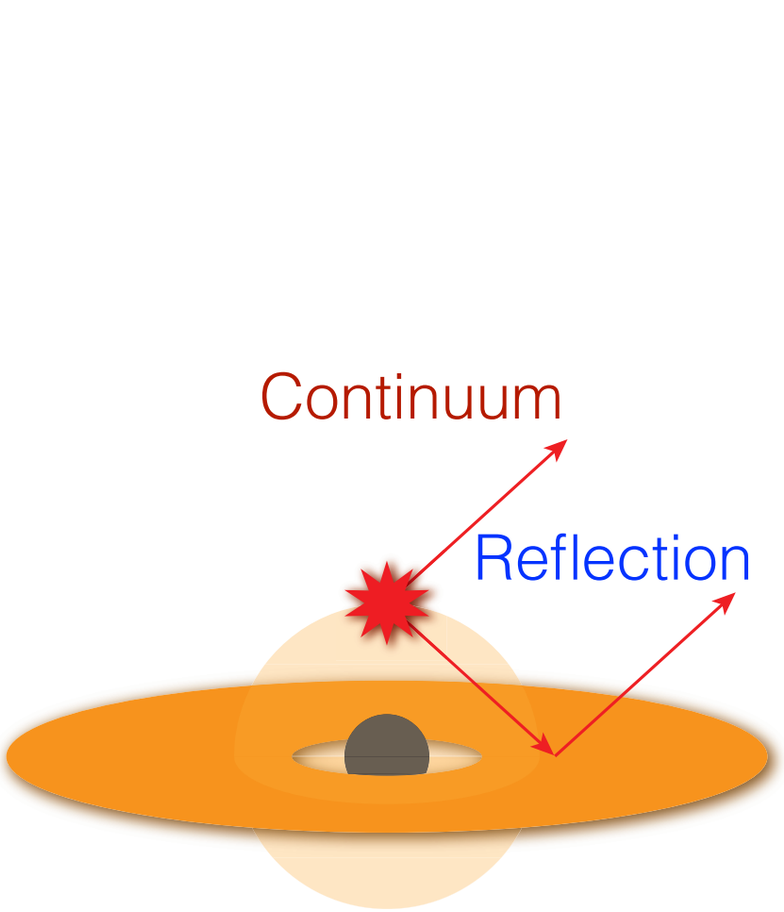
Thermal Emission (Accretion Disc)

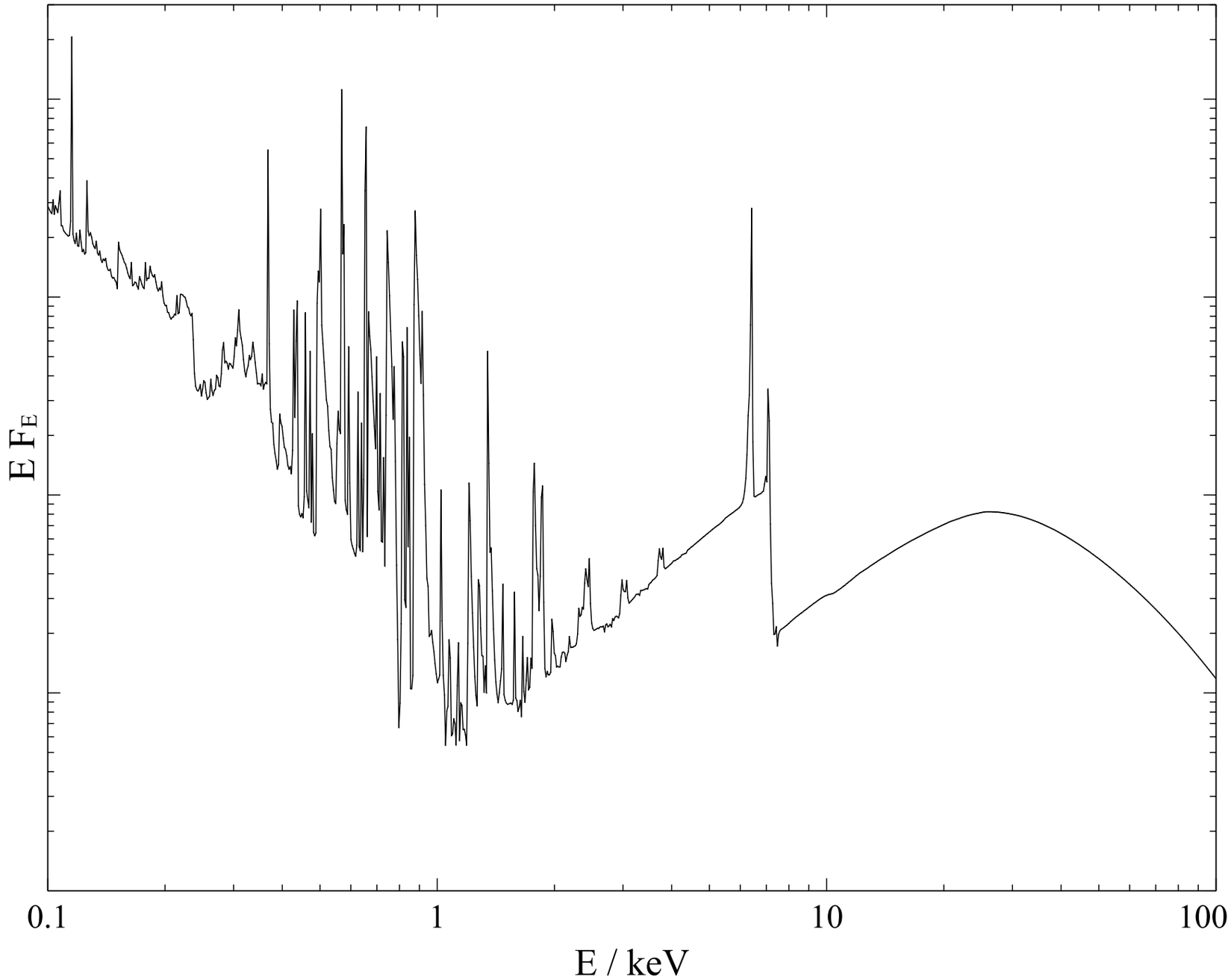
Iron Kα Line

Corona and X-ray Continuum

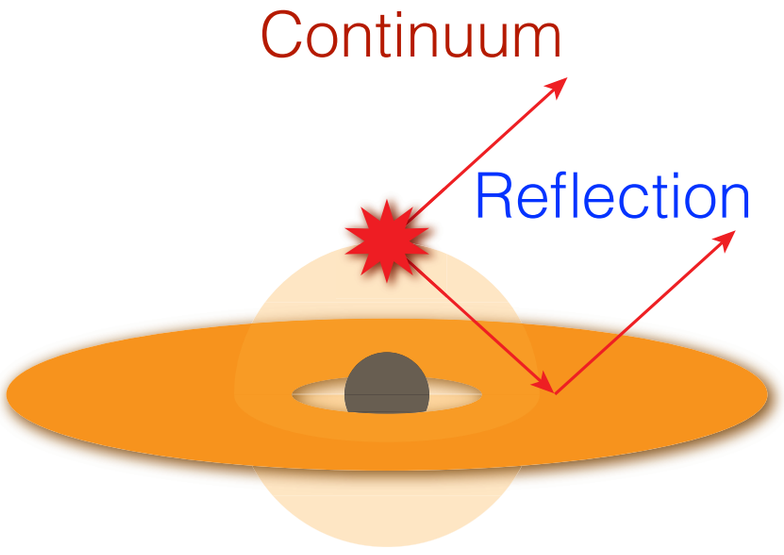


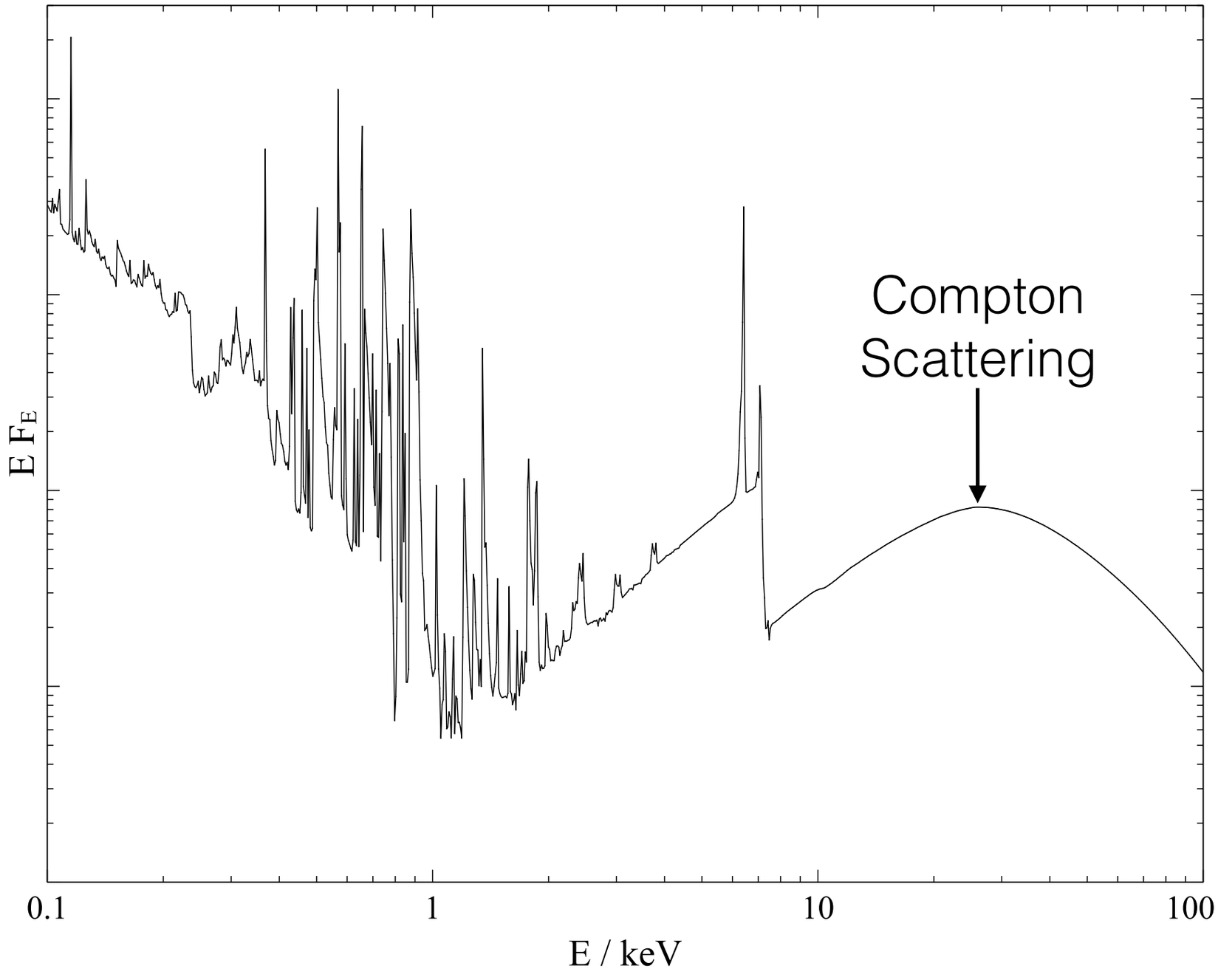
X-ray Reflection



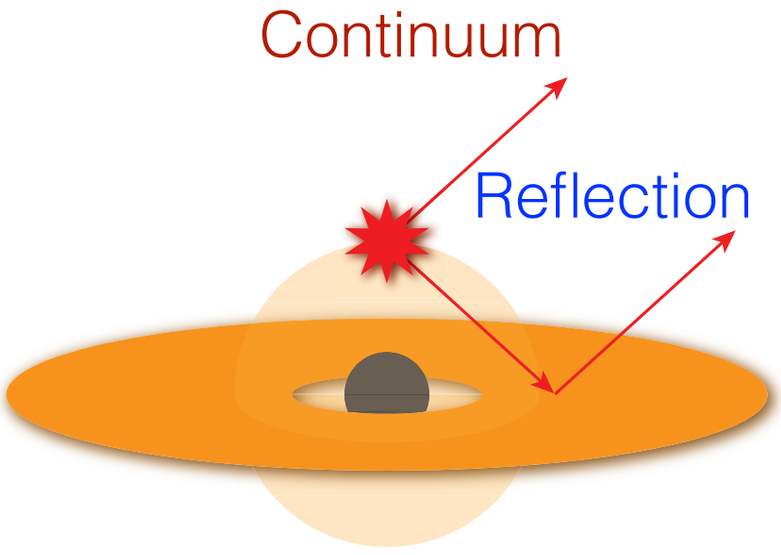


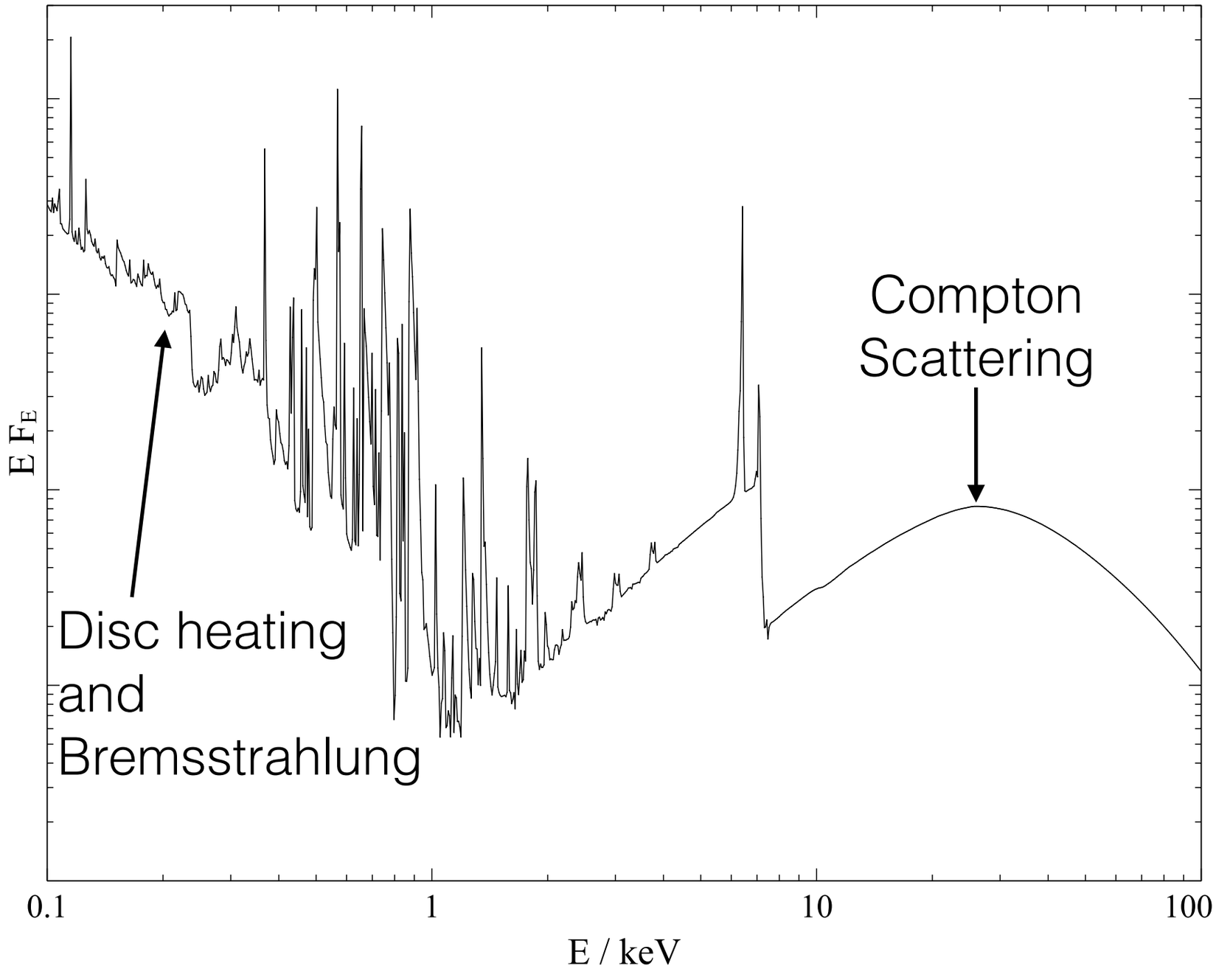
X-ray Reflection





X-ray Reflection





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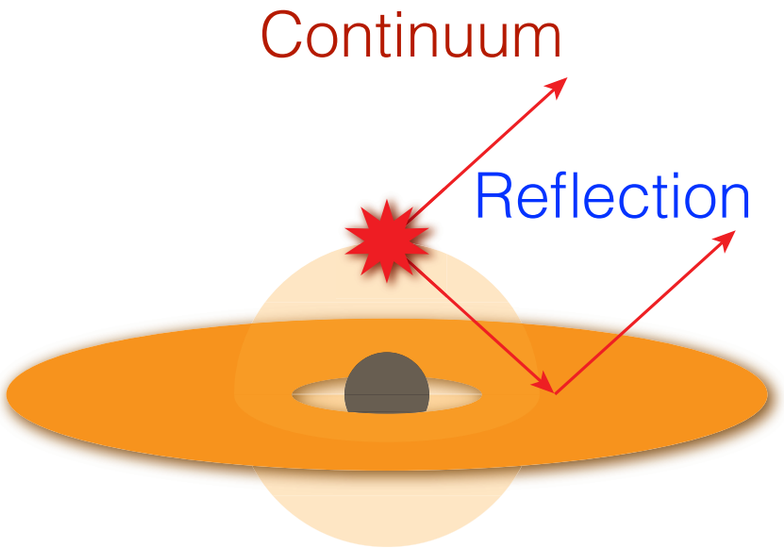

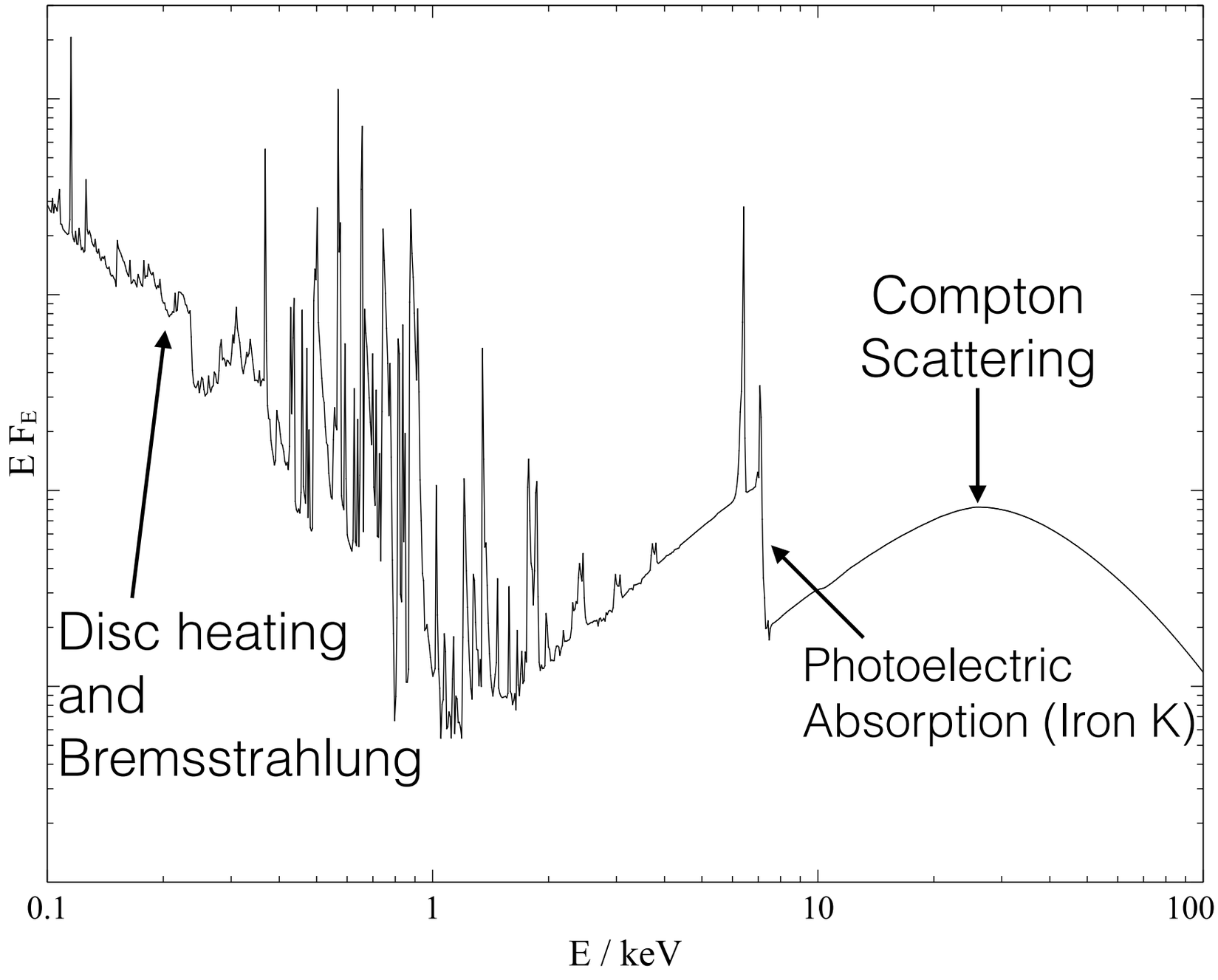

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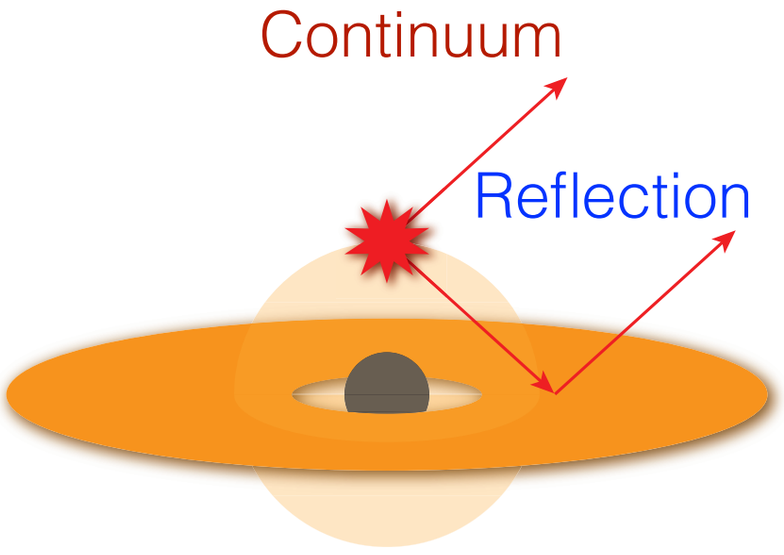

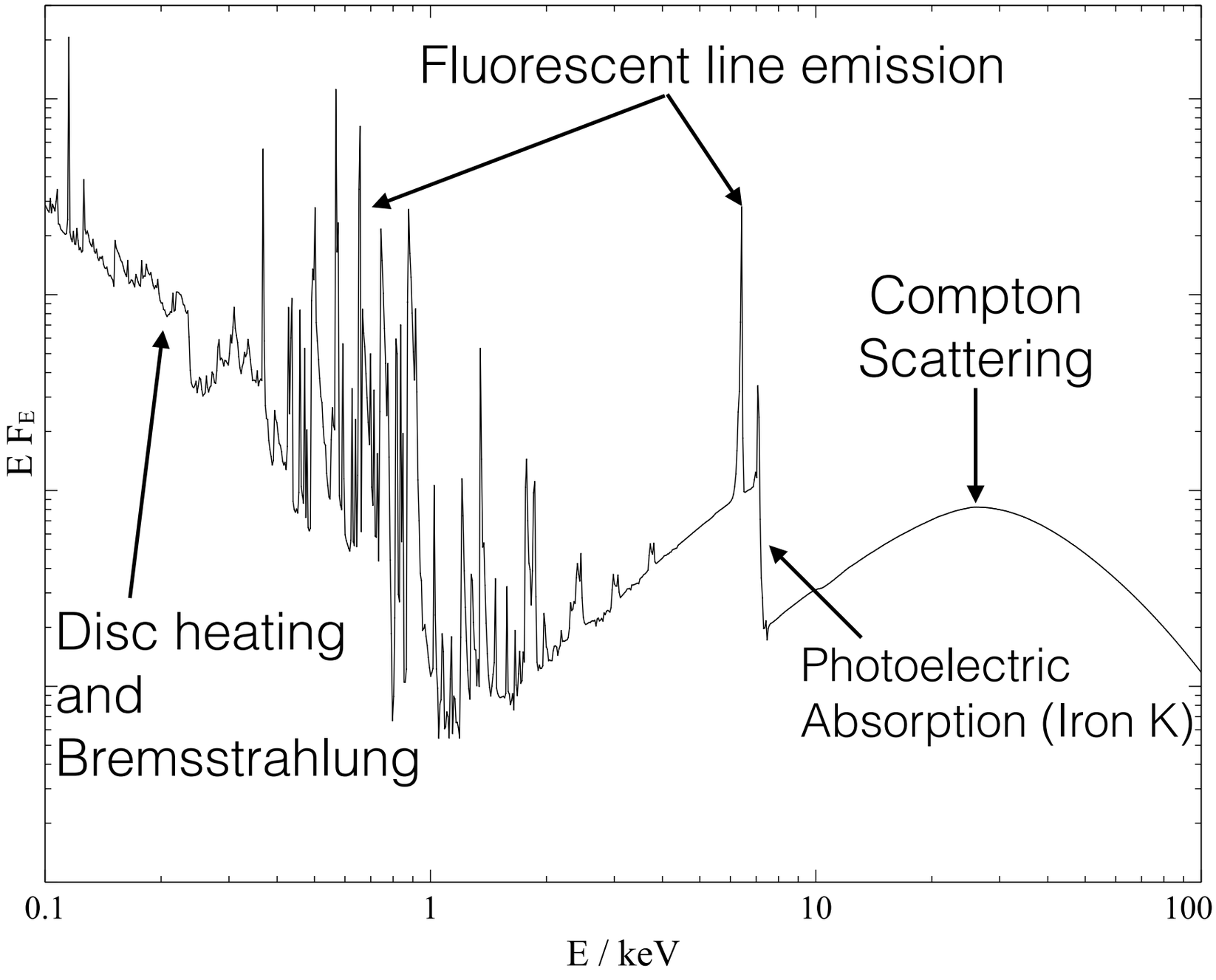

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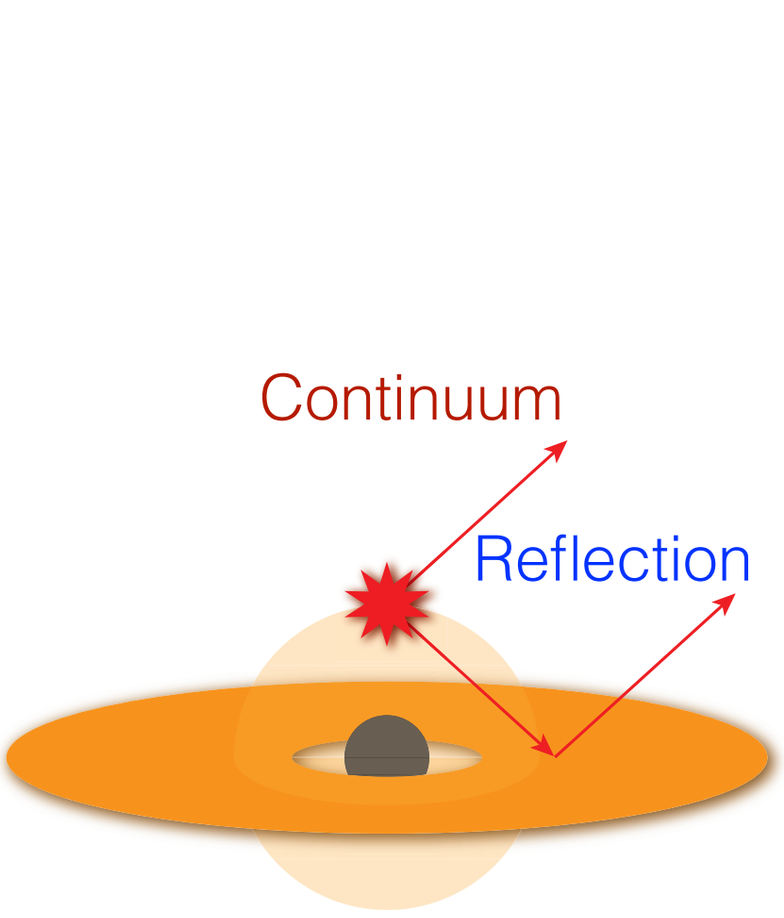

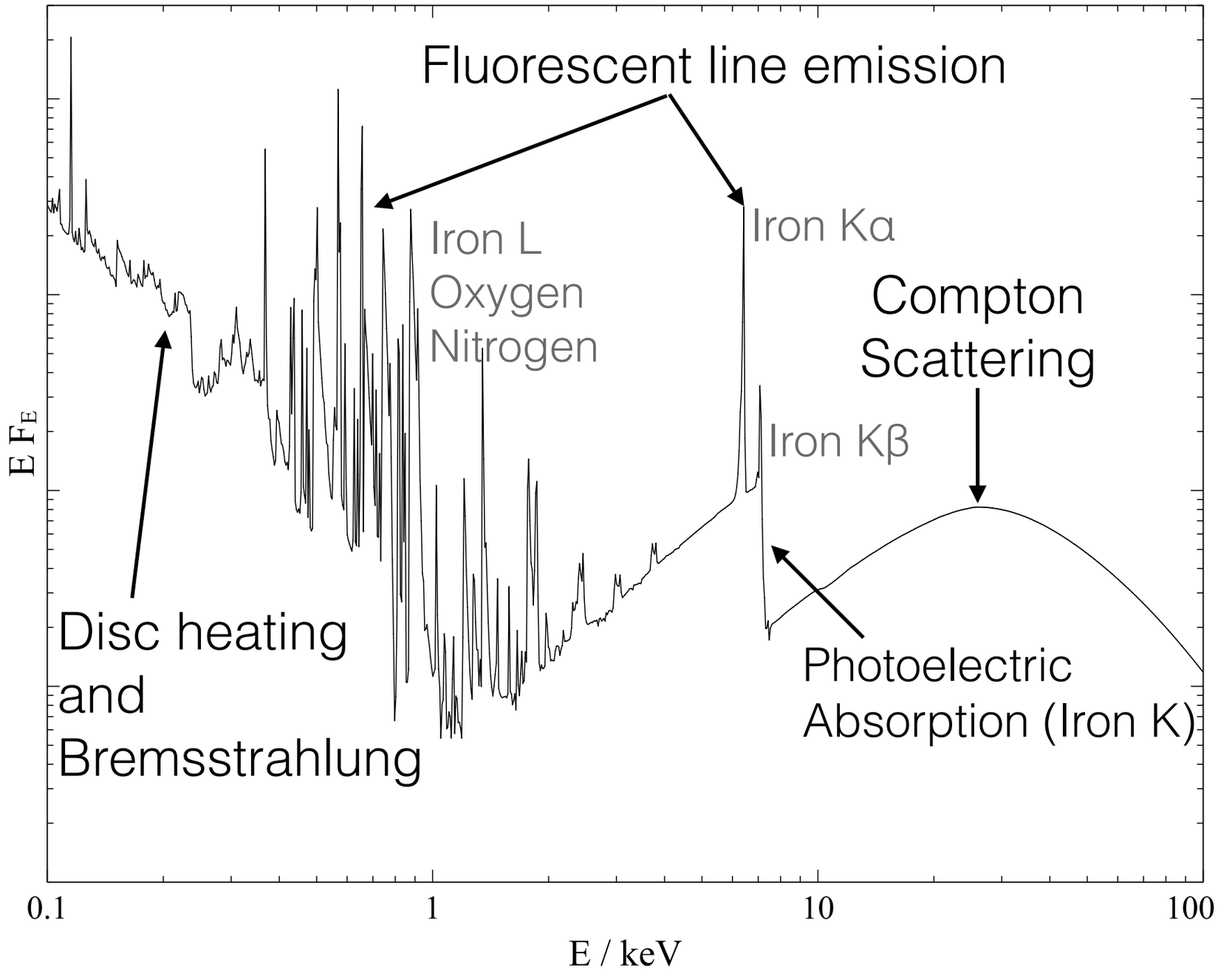

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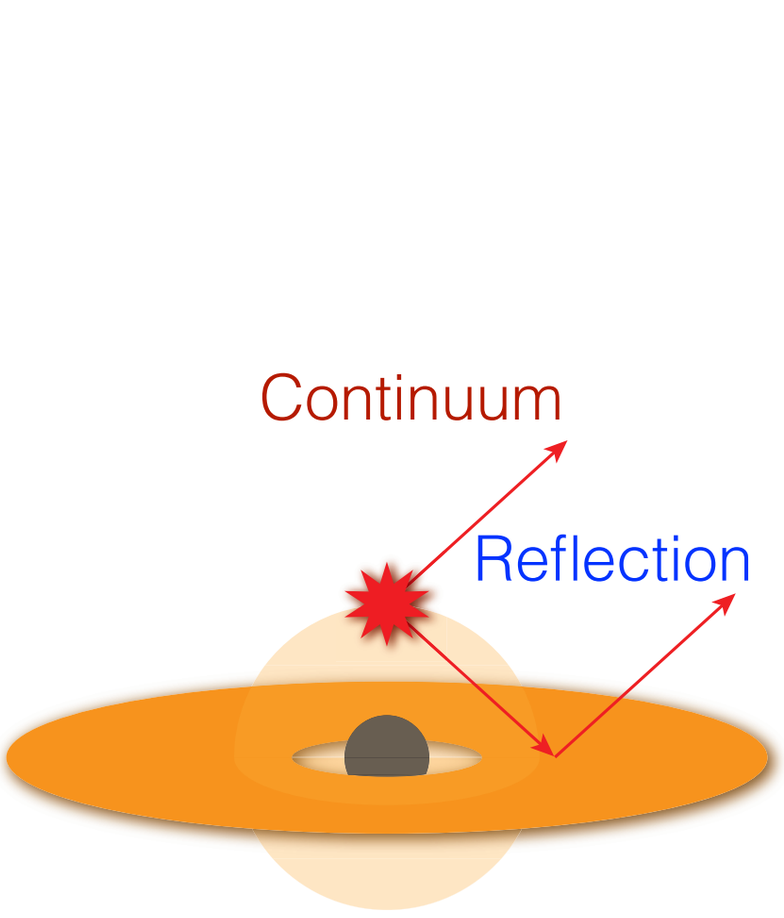
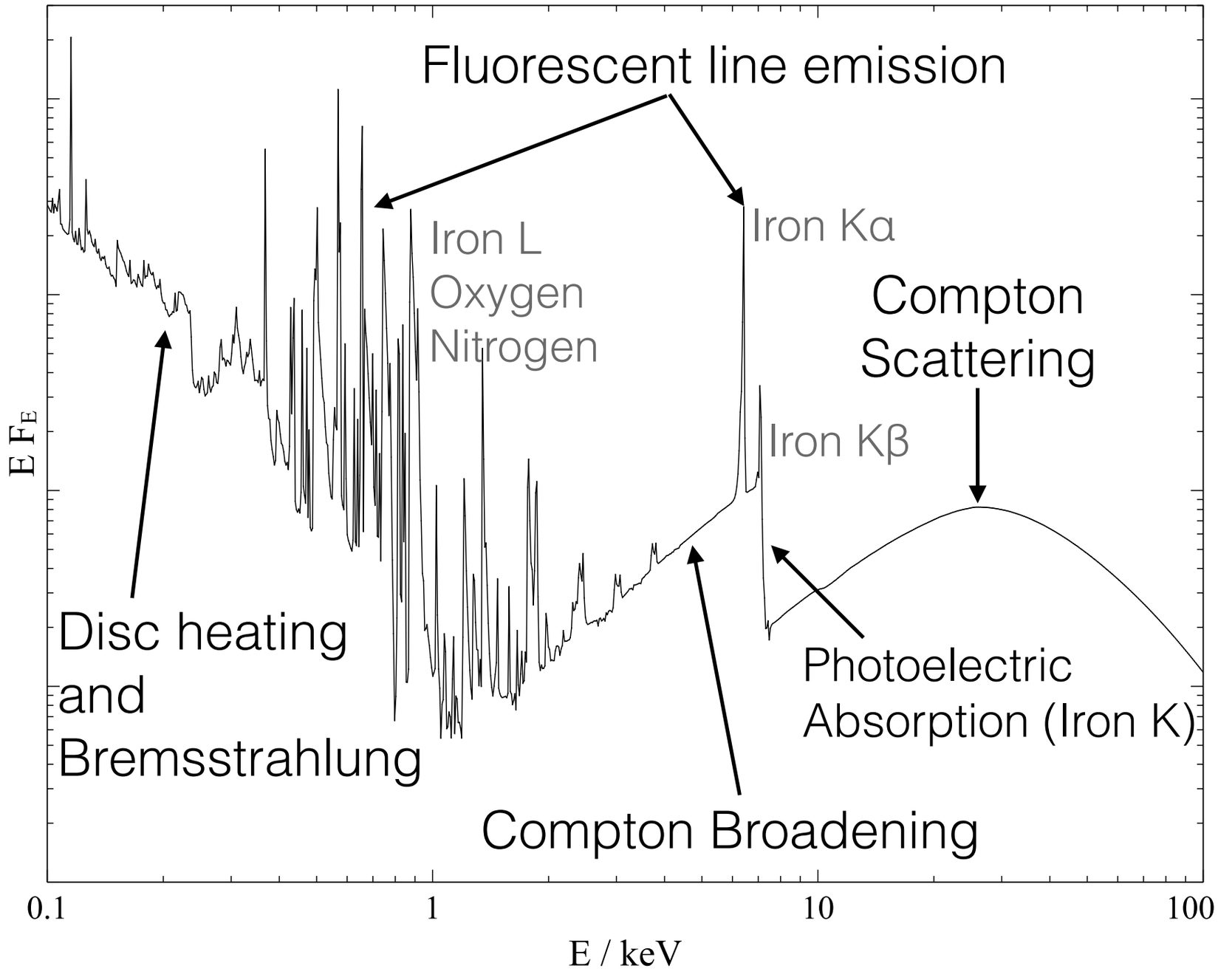
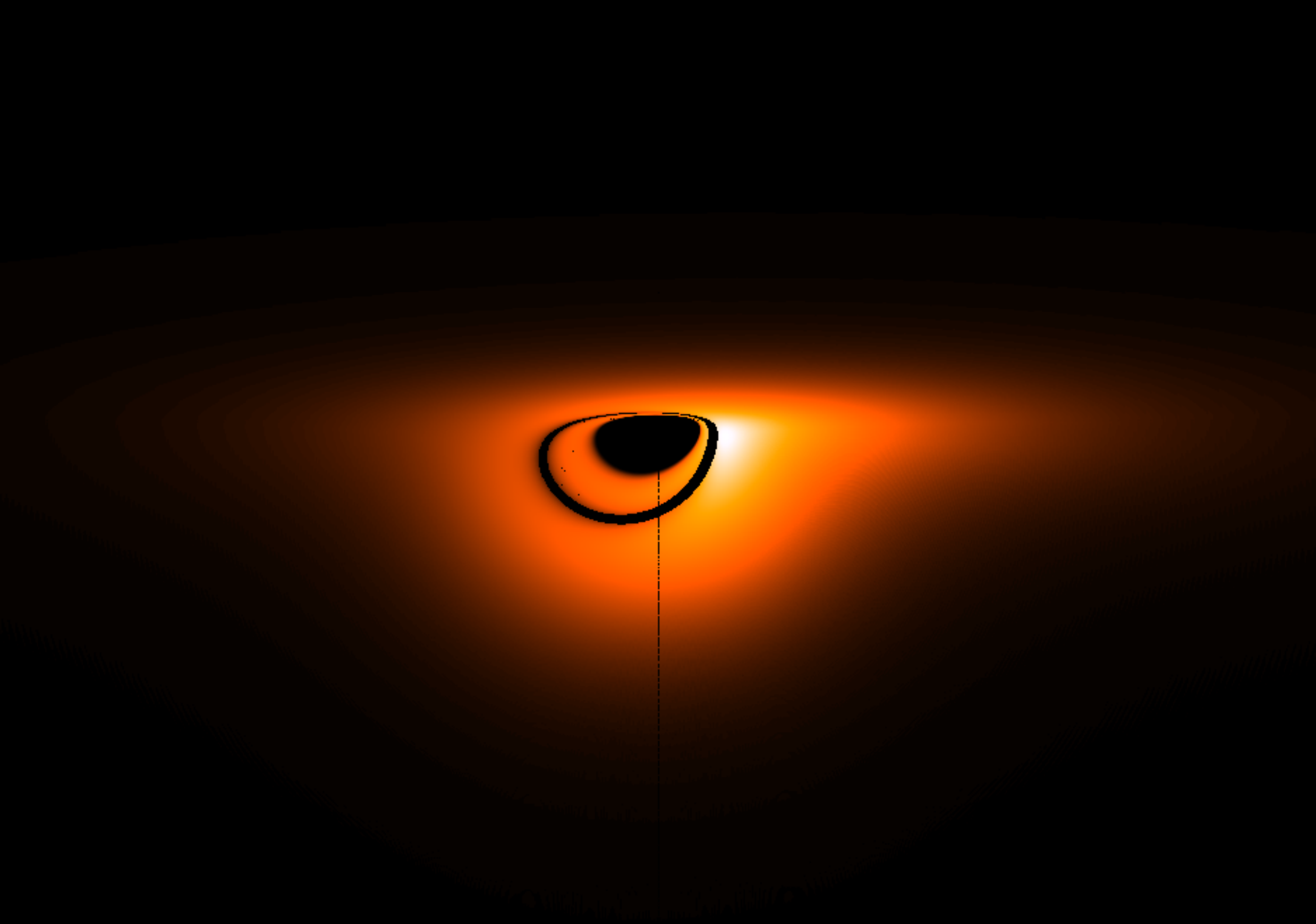
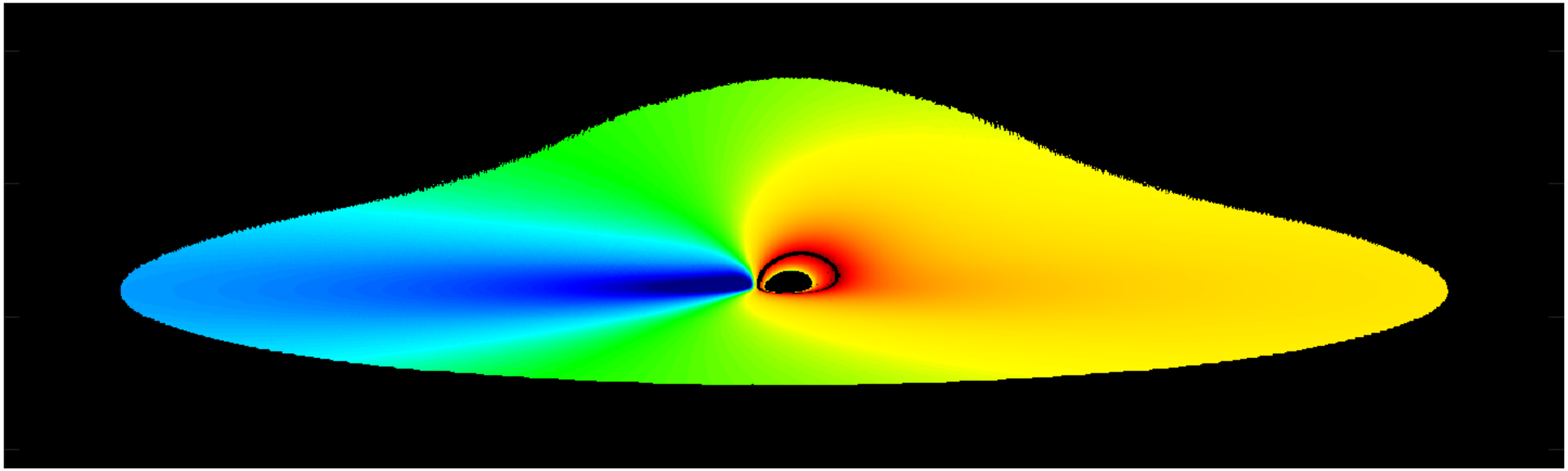
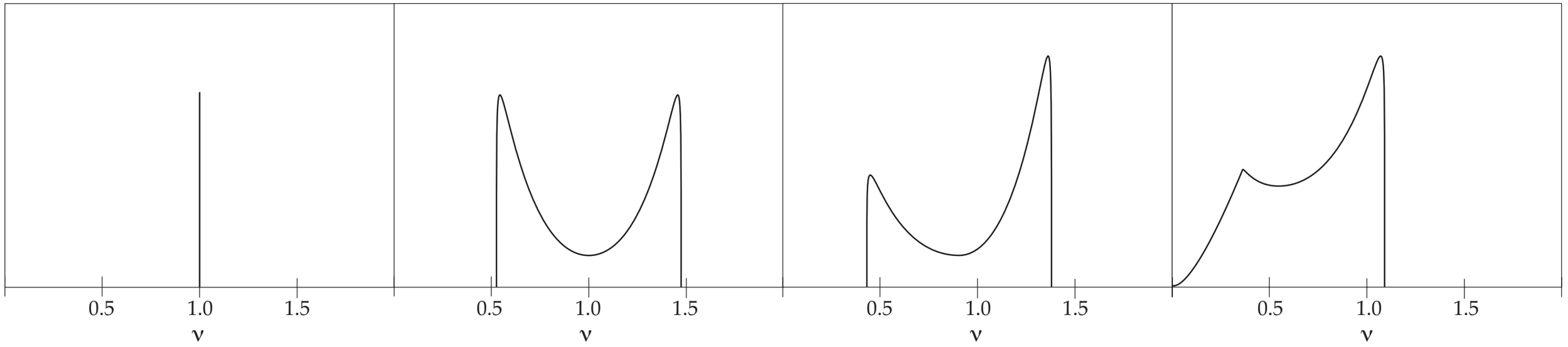










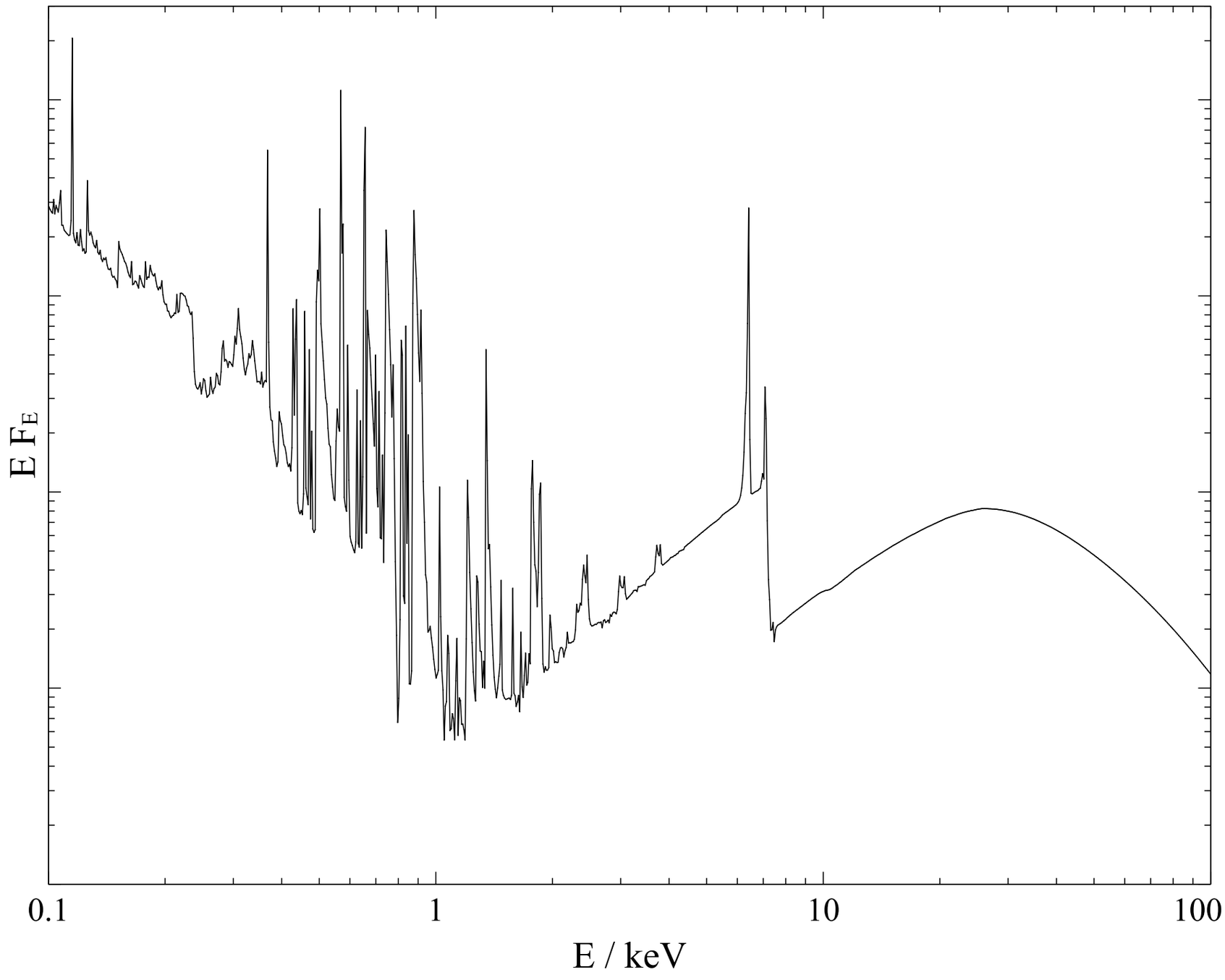
Rest Frame
Emission Line

+ Classical Doppler Shift

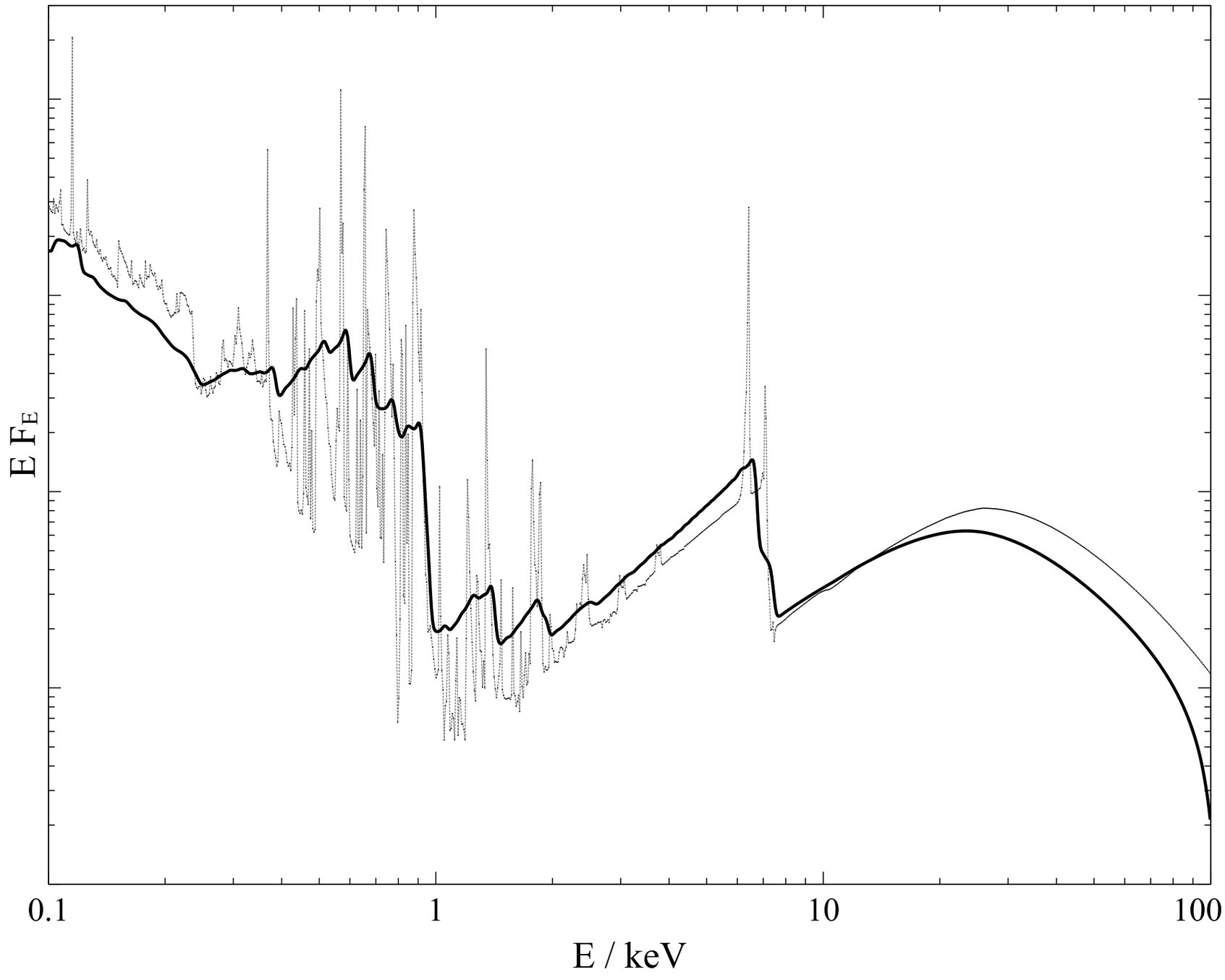
+ Special Relativity
Transverse Doppler Shift
Beaming

+ General Relativity
Gravitational Redshift

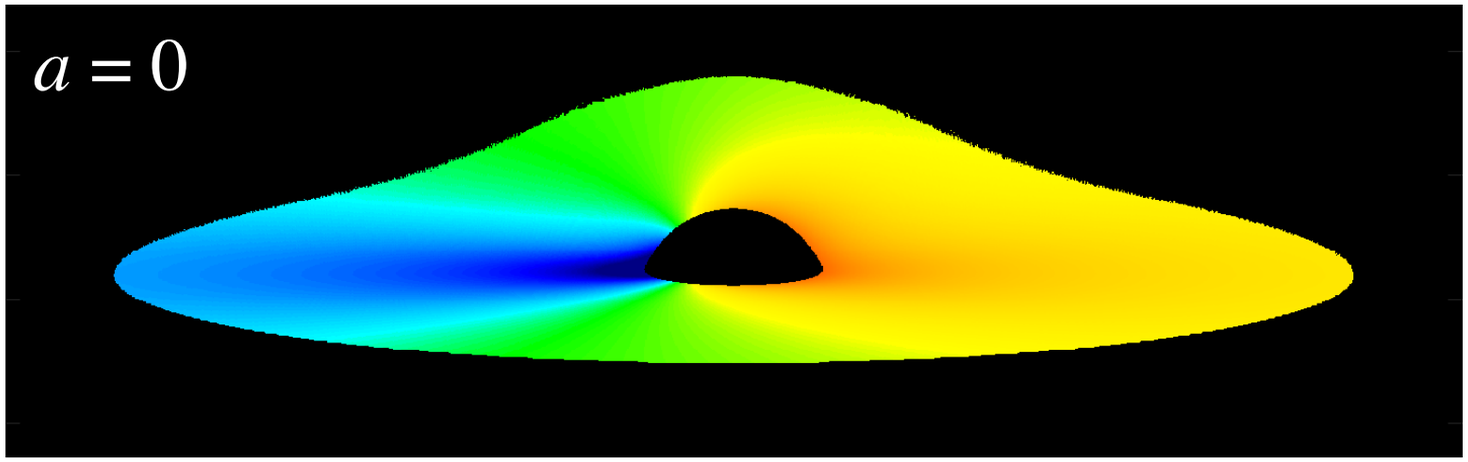
Relativistically Blurred Reflection

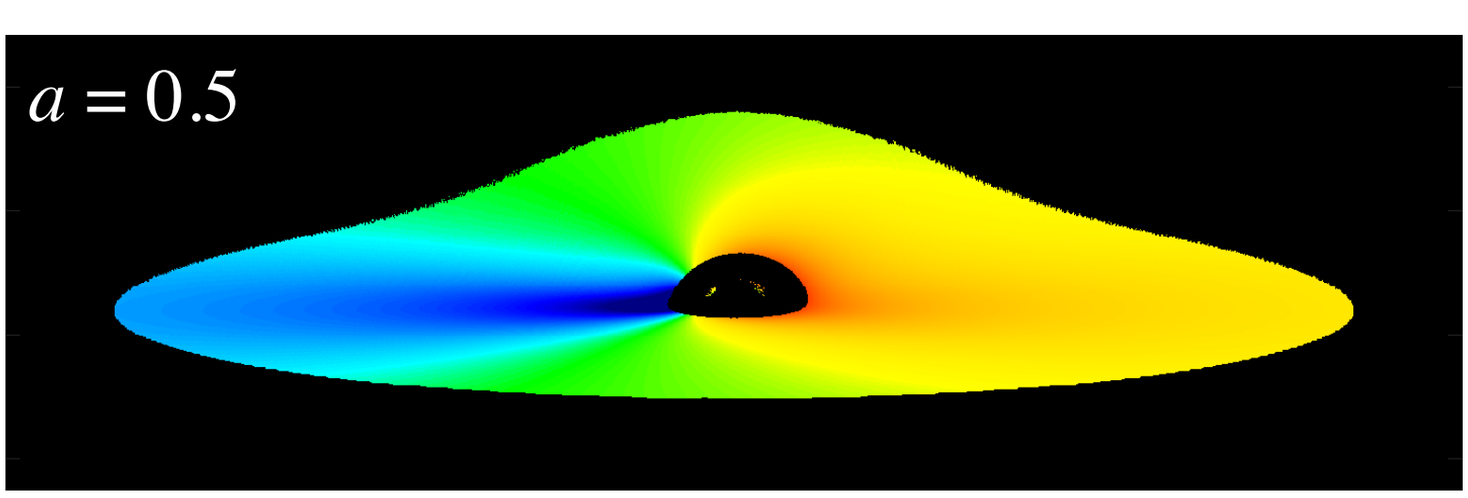


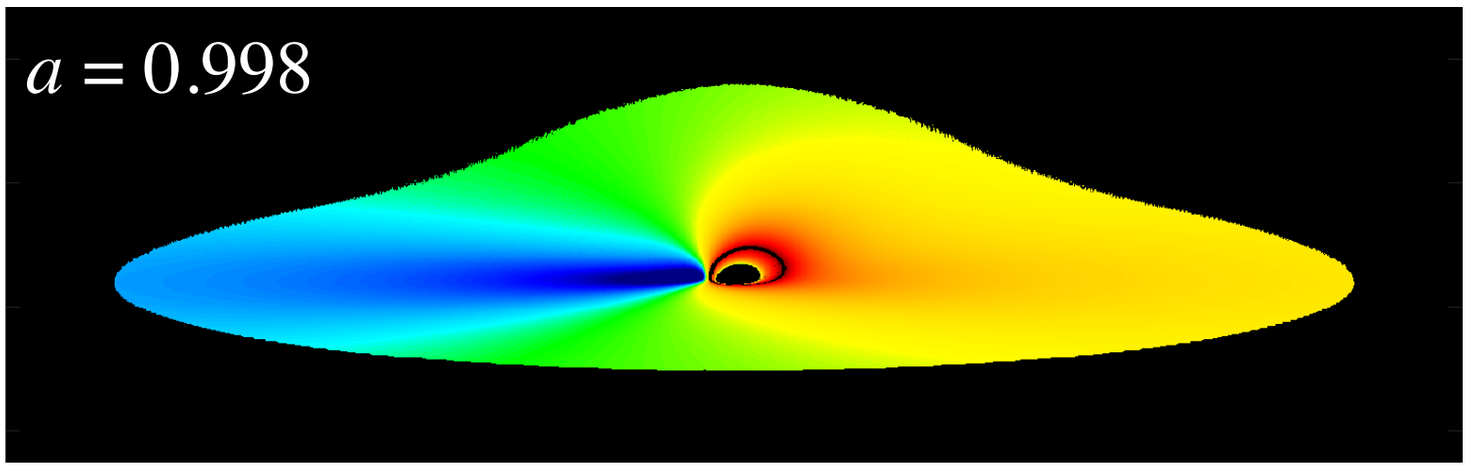
Relativistically Blurred Reflection

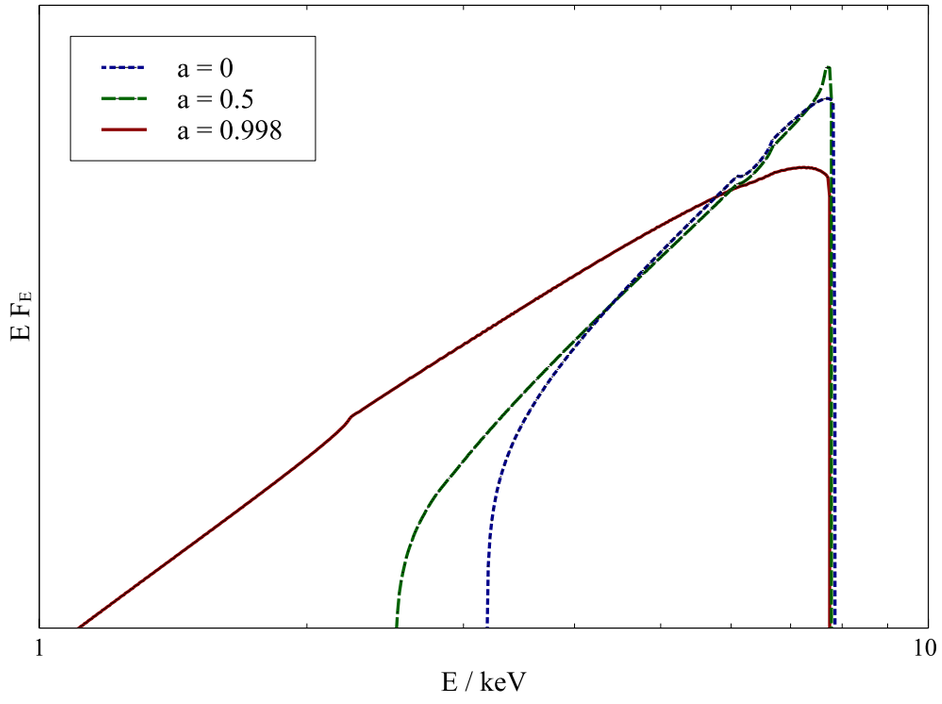


Measuring Black Hole Spin









Summary

dan.wilkins@stanford.edu

- Black holes power some of the most luminous objects in the Universe – liberation of gravitational potential of inflating material

- Observing (accreting) black holes across all wavelengths teaches us about their properties, their environments and the accretion process

- Can apply basic physics to interpret observations – black hole mass, temperature and extent of disc, spin

- Detailed analysis of X-ray spectra and variability and comparison with detailed models lets us understand detailed physics of accretion